

# Neutrinos

## Nature's Mysterious Messengers



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Fermi National Accelerator Laboratory

Ask-a-Scientist Lecture  
June 07, 2015

# Some Neutrino Trivia

Neutrinos are present EVERYWHERE ! In the Sun, in space, traveling through atmosphere, earth, rock, water, cereal, shoes, school bags, smartphones !

One hundred billion of them pass through each of your finger nails every second !

66 billion neutrinos cross a  $\text{cm}^2$  (about size of your eye socket) each second !

They barely interact with matter, like automobiles, dentists or enchiladas !

Even if a neutrino traveled  $10^{16}$  meters through solid lead (a light year), it would have a 50:50 chance of hitting anything along its way !

At the coldest lab temperatures ever achieved, neutrinos could still move at  $\sim 300$  m/s, MORE THAN 20 TIMES AS FAST AS Usain Bolt at top speed !




# Neutrinos .....

Are the most abundant known matter particles in the Universe, outnumbering all other particles by a factor of a **BILLION**




The Sun produces trillions of neutrinos through its nuclear processes that supply it with energy !

About 100 billion solar neutrinos pass through your thumbnails every second !



Carry almost all (~99%) energy from a Supernova explosion !  
Such an explosion can outshine an entire galaxy !

For a gravitational collapse at center of galaxy, expect to see ~ 5000 neutrinos !



Large numbers formed at the time of the Big Bang are still whizzing around the Universe, called “relic neutrinos” !

About 400 /cm<sup>3</sup> or 20,000,000 neutrinos in your space right now !

# Neutrinos also come from .....



Lima Beans



Huh ! How's that ?!!!

Beer



Red Meat

Radioactive elements in them !



Bananas



Brazil Nuts



Potatoes



Carrots

Radioactive decay was how the neutrino was discovered !



# Our Plan For Today

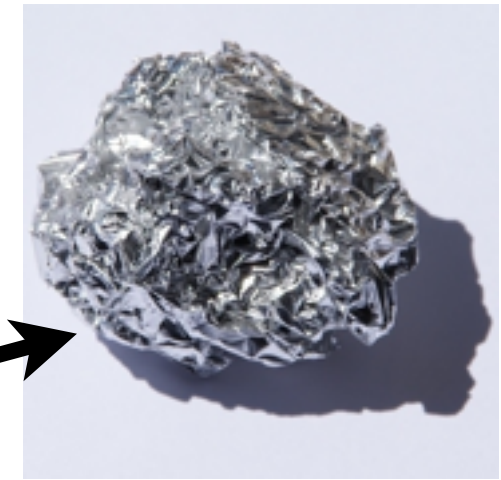
- First, we will take a brief look at **particle physics as a whole** and see where neutrinos fit into the picture.
- Second, we'll explore the **fascinating history of the neutrino**, its existence, its discovery and the surprises it brings.
- Then we'll take a look at **neutrino experiments at Fermilab** and probe the questions that we are addressing here.
- Lastly we will find out what the **neutrino might reveal** about the beginnings of our universe !
- And how should we explore this ?



# Elements → Atoms

## Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																
1 <b>H</b> Hydrogen 1.00794	<div>Atomic # Symbol Name Atomic Mass</div> <div><div><div>C Solid</div><div>Hg Liquid</div><div>H Gas</div><div>Rf Unknown</div></div><div><div>Alkali metals</div><div>Alkaline earth metals</div><div>Lanthanoids</div><div>Actinoids</div><div>Transition metals</div><div>Poor metals</div><div>Other nonmetals</div><div>Noble gases</div></div></div>																2 <b>He</b> Helium 4.002602																
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182																	10 <b>Ne</b> Neon 20.1797															
11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050																	18 <b>Ar</b> Argon 39.948															
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.887	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938045	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933195	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.796																
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.96	43 <b>Tc</b> Technetium (97.9072)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.290																
55 <b>Cs</b> Cesium 132.9054519	56 <b>Ba</b> Barium 137.327																	86 <b>Rn</b> Radon (222.0175)															
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)																	118 <b>Uuo</b> Ununoctium (294)															
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.																																	
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). <a href="http://www.ptable.com/">http://www.ptable.com/</a>																																	
57 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.90768	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.054	71 <b>Lu</b> Lutetium 174.967																			
89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.03806	91 <b>Pa</b> Protactinium 231.03688	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)																			



Aluminum (Al) foil



Copper (Cu) wires



Sodium (Na)  
in table salt



Iron (Fe) in Meteorite



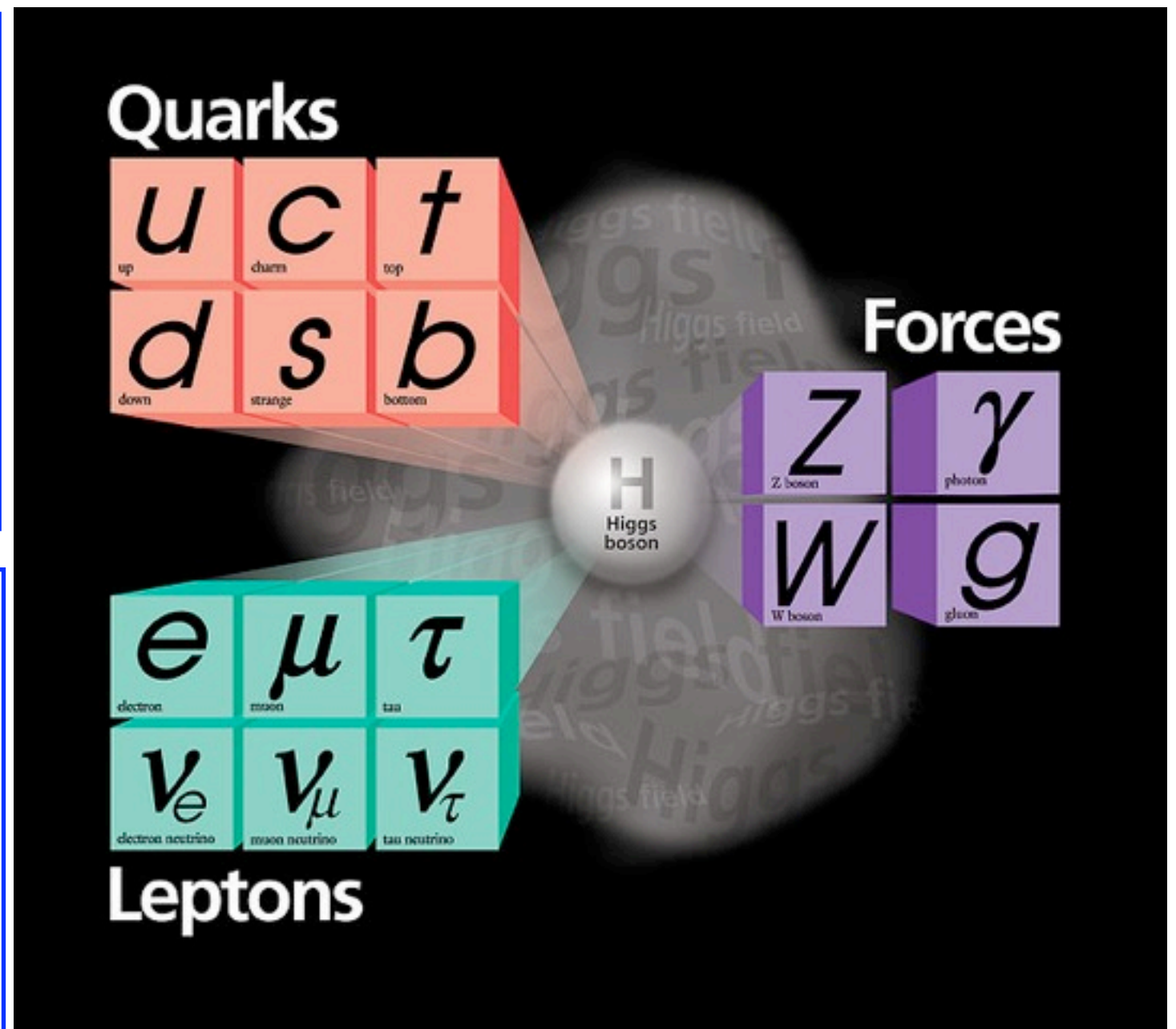
# Building Blocks of Particle Physics

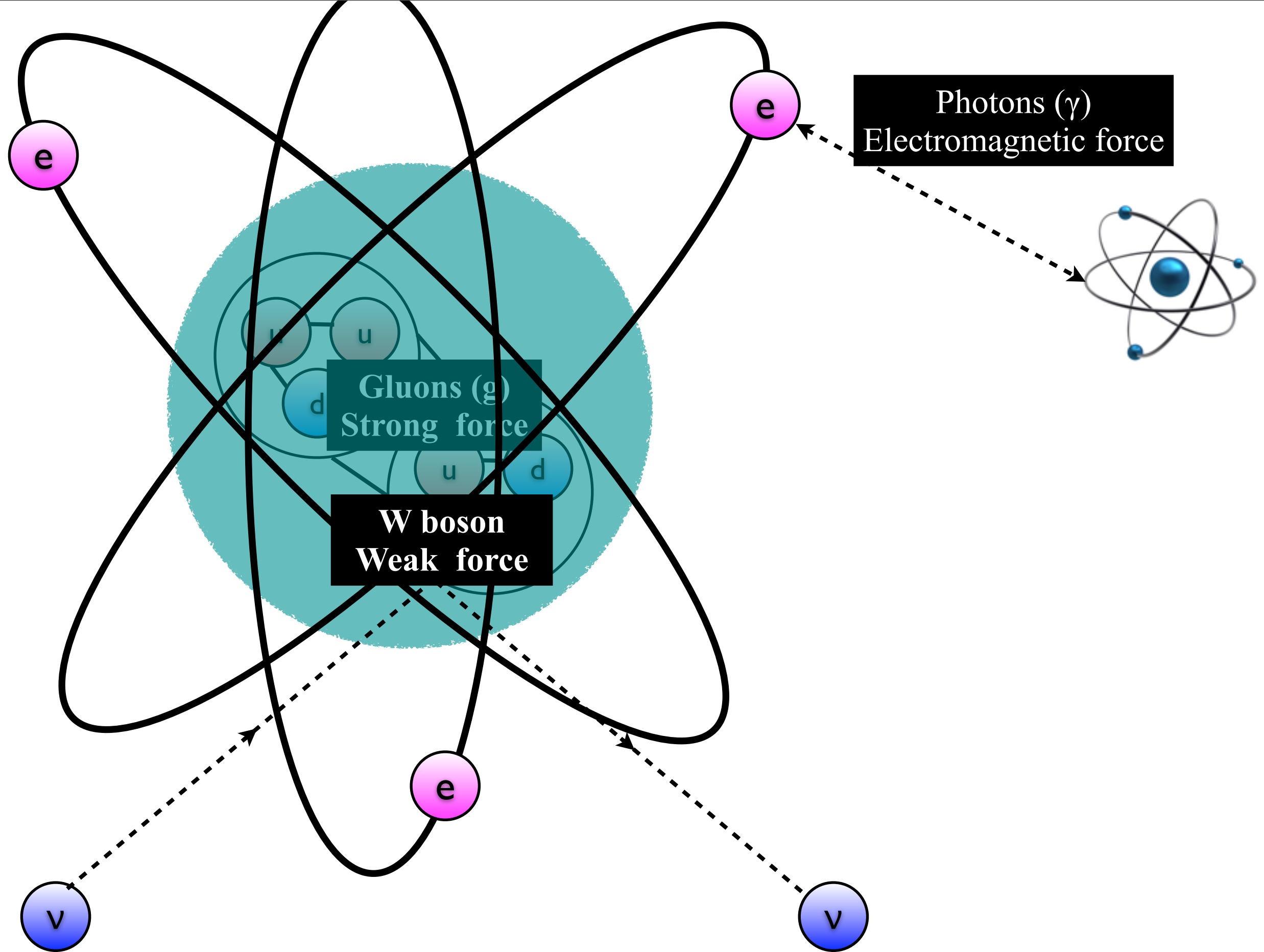
- 12 matter particles

- 6 quarks
- 6 leptons
- these 12 form the building blocks of the “usual” matter in the Universe

- 4 forces

- gravitational force
- electromagnetic force
- strong nuclear force
- weak nuclear force
- these 4 ways for particles to interact with each other are the ones we know of at present.



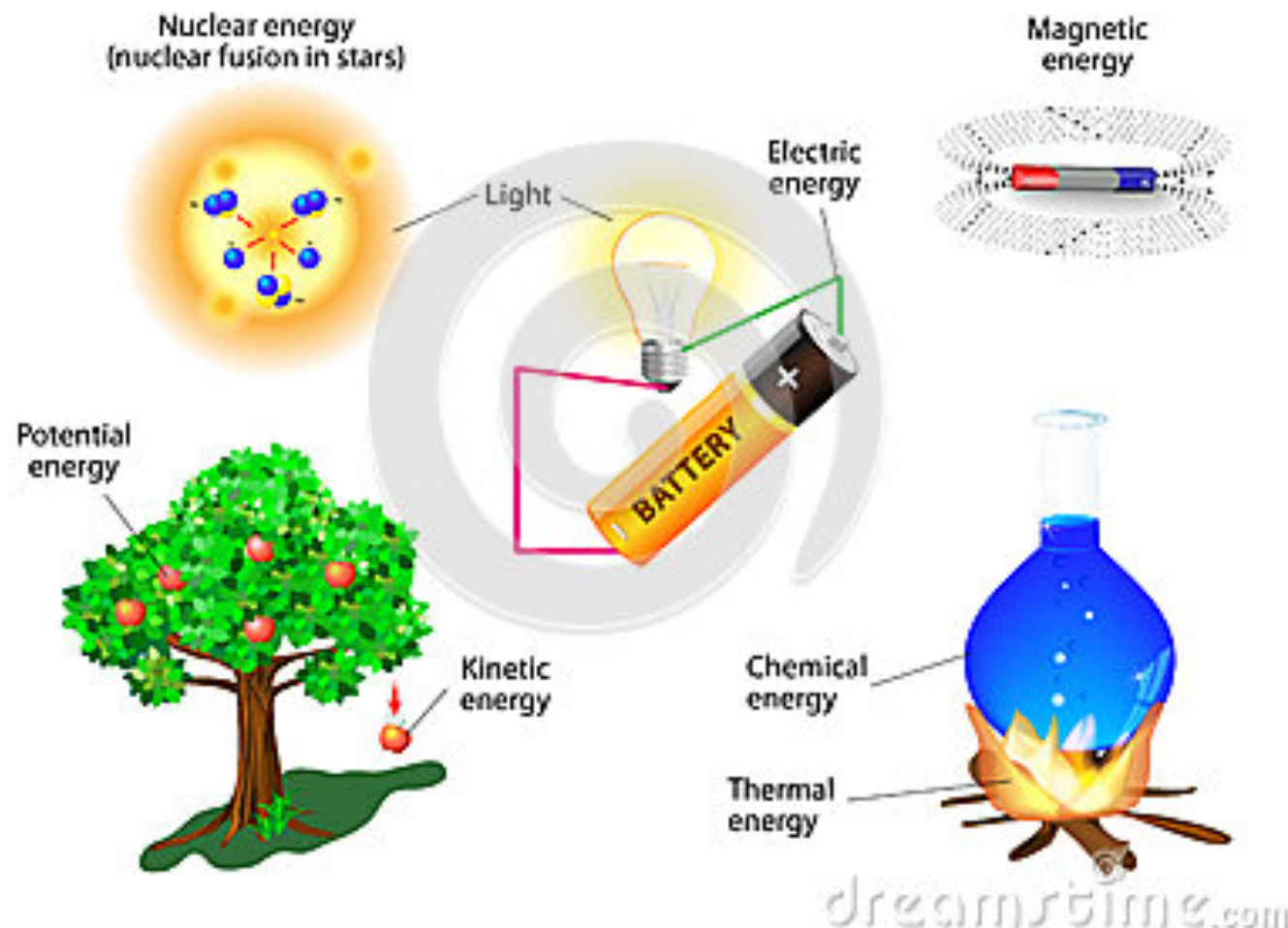




# Energy Conservation

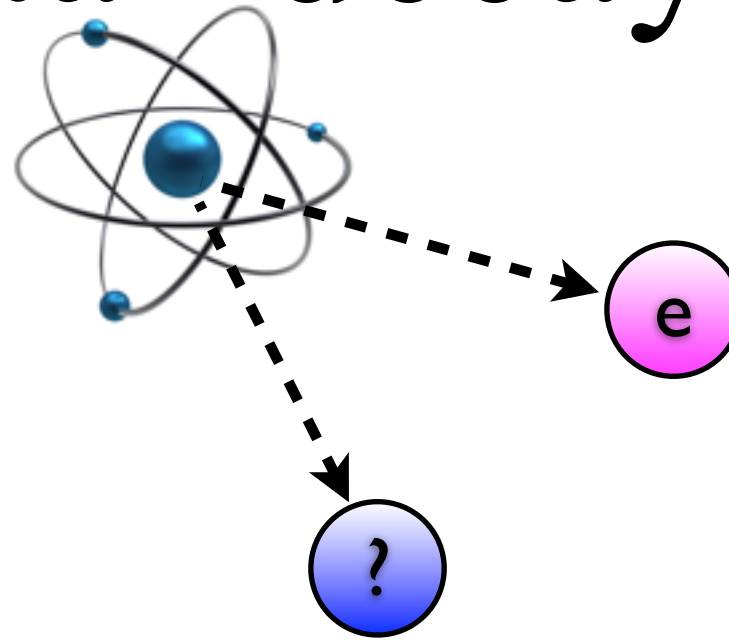
- Energy-mass relation:  $E^2 = p^2c^2 + m^2c^4$
- Energy is conserved overall.
- Profound way of storing and transforming energy.

## FORMS OF ENERGY

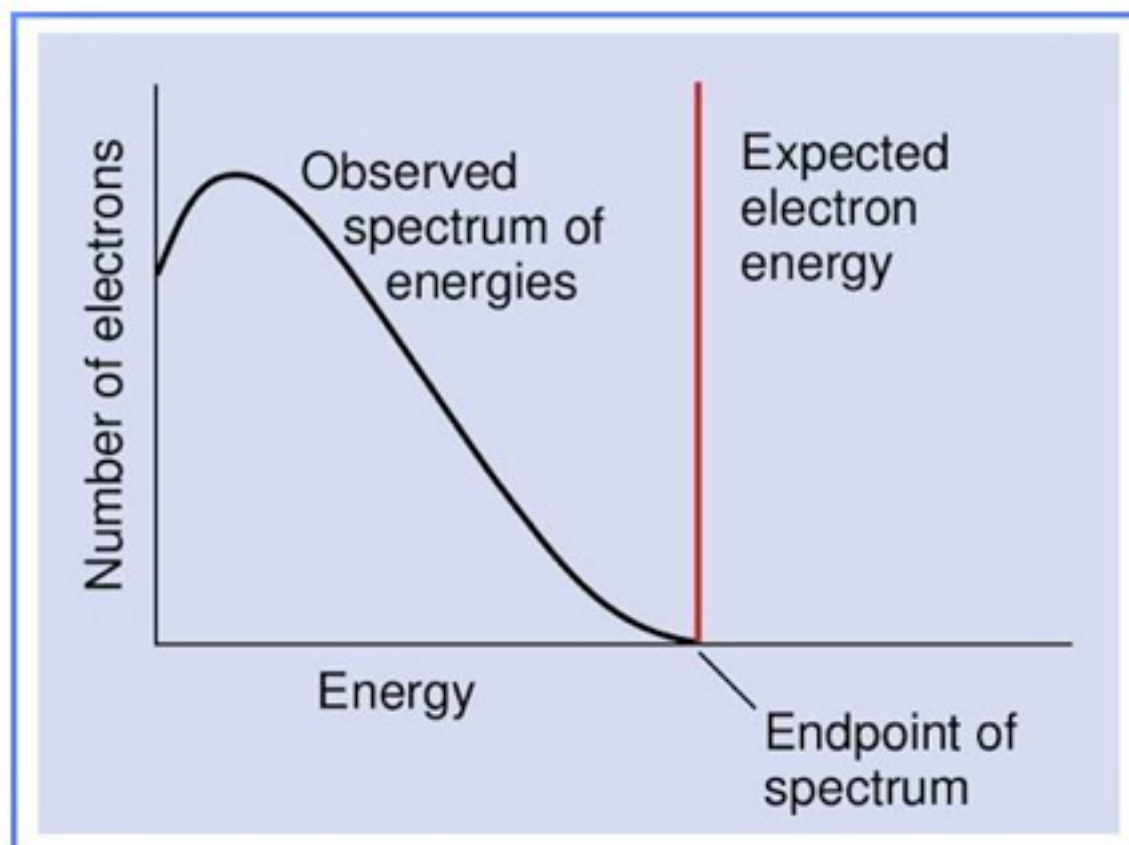


"THAT'S IT? MONTHS OF STUDY, ENDLESS REPORTS, AND ALL WE COME UP WITH IS 'EVERYONE SHOULD STAY HOME' MORE?"

# The “Beta” decay crisis



A neutron could change into a proton by emitting a “beta” (electron) and what ?



In 1914, James Chadwick discovered that energy spectrum of the betas was **continuous and not a single value !**

Did the principal of conservation of energy not hold, after all ?



# Pauli's Desperate Remedy

circa 1930

- In “beta” decays the electron is accompanied by an additional neutral particle.
  - So energy is conserved. It is just shared, between the visible “beta” electron and the invisible neutral partner.
- Pauli intended to provide two solutions:
  - Understand the properties of neutrons in nuclei.
  - Mitigate the “beta” decay crisis by predicting a new particle !
- Thus, the idea of the existence of a neutrino was born !



Pauli on vacation, 1931

original - Photocopy of PLC 0393  
Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der  
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut  
der Eidg. Technischen Hochschule  
Zürich

Zürich, 4. Dez. 1930  
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst  
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich  
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie  
des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg  
verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz  
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale  
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,  
welche den Spin  $1/2$  haben und das Ausschliessungsprinzip befolgen und  
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie  
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen  
müsste von derselben Grössenordnung wie die Elektronenmasse sein und  
jedemfalls nicht grösser als 0,01 Protonenmasse. - Das kontinuierliche  
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim  
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert  
wird, derart, dass die Summe der Energien von Neutron und Elektron  
konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die  
Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint  
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer  
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein  
magnetischer Dipol von einem gewissen Moment  $\mu$  ist. Die Experimente  
verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons  
nicht grösser sein kann, als die eines gamma-Strahls und darf dann  
wohl nicht grösser sein als  $e \cdot (10^{-13} \text{ cm})$ .

Ich traue mich vorläufig aber nicht, etwas über diese Idee  
zu publizieren und wende mich erst vertrauensvoll an Euch, liebe  
Radioaktive, mit der Frage, wie es um den experimentellen Nachweis  
eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa  
10mal grösseres Durchdringungsvermögen besitzen würde, wie ein  
gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein  
wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn  
sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt,  
gemäss und der Ernst der Situation beim kontinuierlichen beta-Spektrum  
wird durch einen Ausspruch meines verehrten Vorgängers im Amt,  
Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat:  
"O, daran soll man am besten gar nicht denken, sowie an die neuen  
Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren. -  
Also, liebe Radioaktive, prüfet, und richtet. - Leider kann ich nicht  
persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht  
vom 6. zum 7. Dez. in Zürich stattfindenden Balles hier unabkömmlich  
bin. - Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer  
untertänigster Diener

ges. W. Pauli

Open letter to the group of radioactive people at the  
Gauverein meeting in Tübingen.

Copy

Physics Institute  
of the ETH  
Zürich

Zürich, Dec. 4, 1930  
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more  
detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I  
have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of  
conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral  
particles, which I will call neutrons, that have spin  $1/2$  and obey the exclusion principle and that further  
differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons  
should be of the same order of magnitude as the electron mass and in any event not larger than 0.01  
proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta  
decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and  
electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the  
neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron  
at rest is a magnetic dipole with a certain moment  $\mu$ . The experiments seem to require that the ionizing  
effect of such a neutron can not be bigger than the one of a gamma-ray, and then  $\mu$  is probably not  
allowed to be larger than  $e \cdot (10^{-13} \text{ cm})$ .

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear  
radioactive people, with the question of how likely it is to find experimental evidence for such a neutron  
if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen  
those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of  
the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my  
honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this  
at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive  
people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am  
indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to  
you, and also to Mr. Back, your humble servant

signed W. Pauli



“I have done a terrible thing. I have postulated a particle that cannot be detected.” (W. Pauli, 1931)

Pauli's enthusiasm died quickly - proposed particle should be massless !



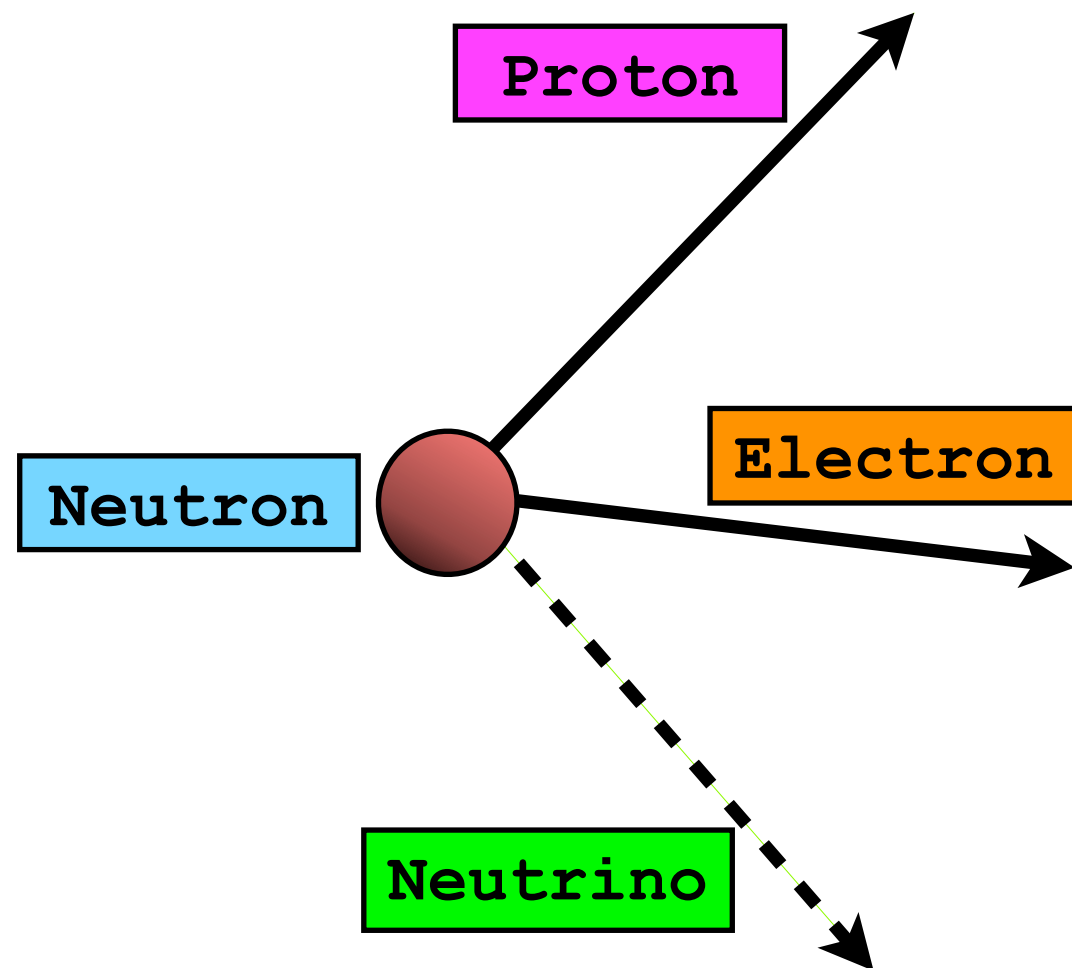
Wolfgang Pauli



Enrico Fermi expressed interest in Pauli's idea and called the proposed neutral particle a “neutrino” (little neutron in Italian).

Enrico Fermi

Fermi's theory assumed that the neutron decays into a proton, an electron ("beta") and a neutrino.



"Beta" decay process

Electron is called "beta" particle

Neutrino bears the invisible energy

Fermi's calculations matched experimental data for the electron energy spectrum !

Sadly, no interest for neutrino topics at the time !

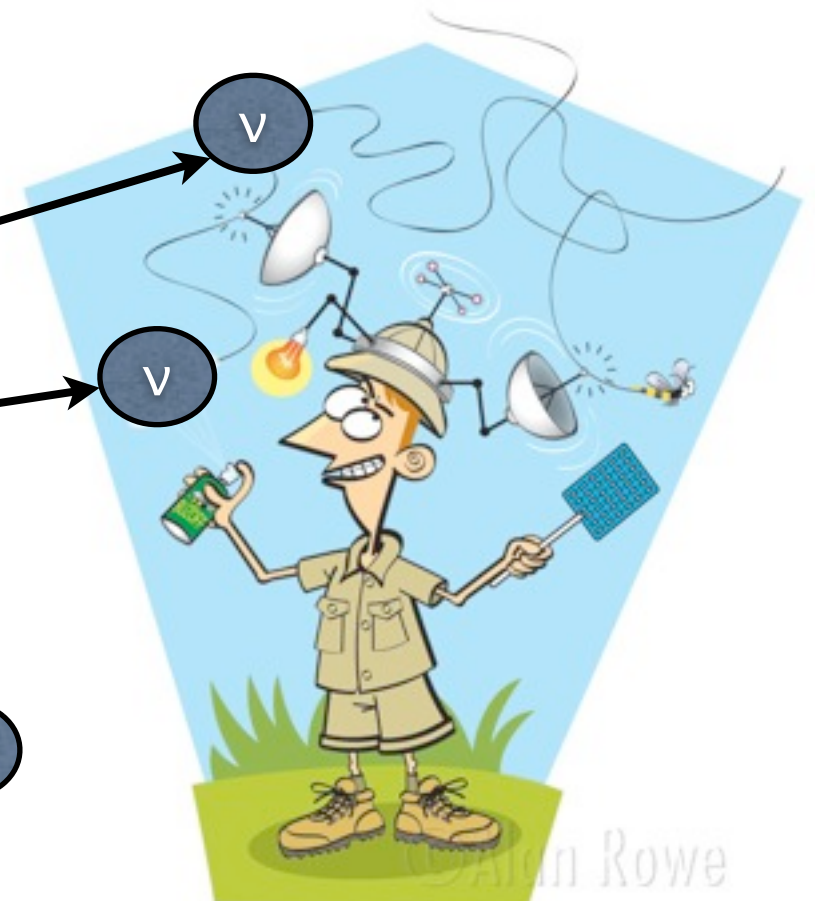


# How do you catch a neutrino ?

- Chances of detecting an individual neutrino are miniscule !
- However if you produce billions of neutrinos per second, you might record one or two occasionally !
- An intense source of neutrinos is a uranium reactor. It produces **ten million billion neutrinos per second** while giving nuclear power !
- Need patience and the right kind of detector to catch at least a few !



This is like winning the lottery !!!



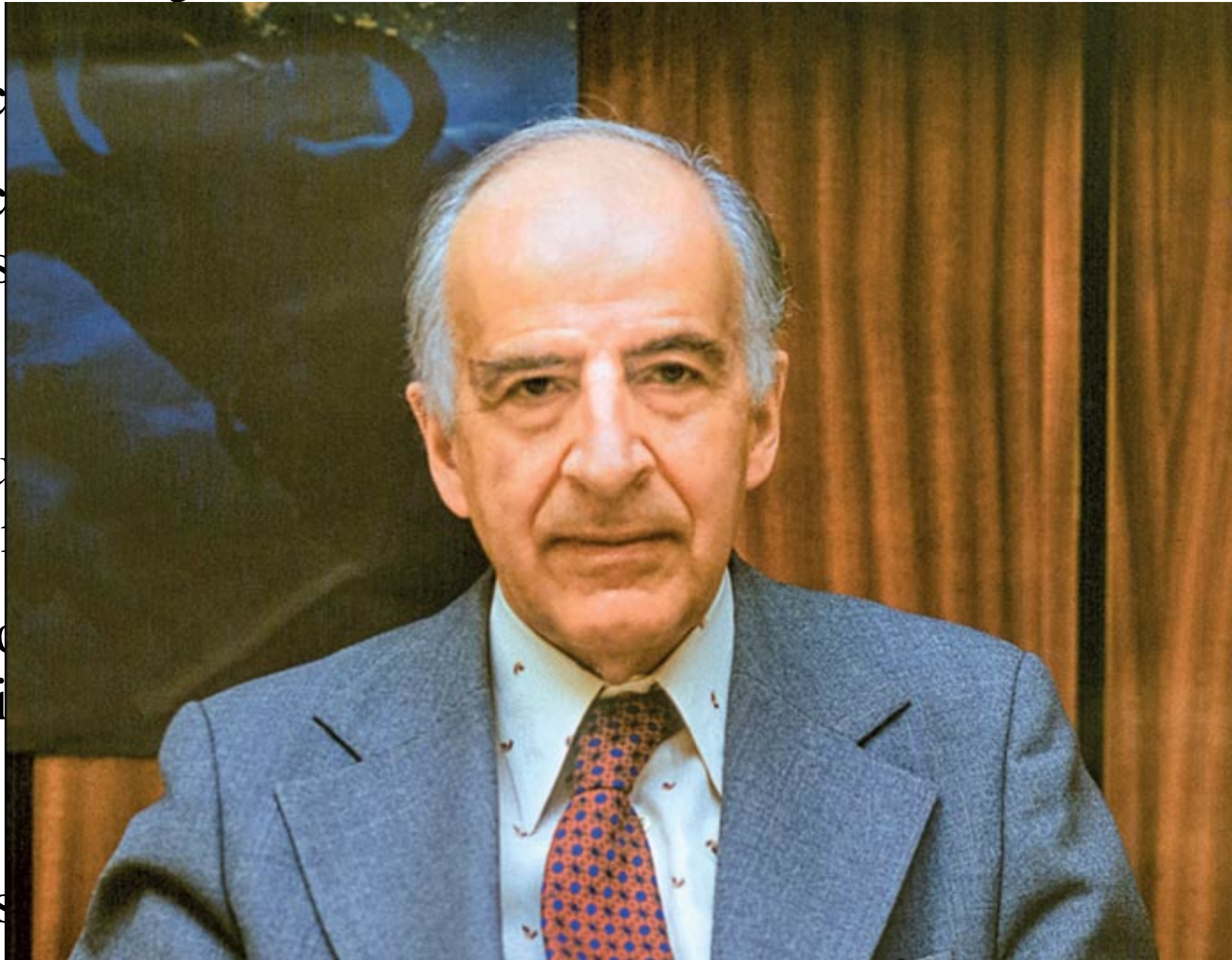
# Can you see a neutrino ?

- You cannot see neutrinos directly !
- You can detect them only if they interact with matter such as atoms, nuclei, protons, neutrons.
- If you produce billions of neutrinos per second, you might catch one or two occasionally !
- Use lots of matter in your detector for maximizing the chances of neutrinos interacting.
- Intense neutrino beams and nuclear reactors are copious sources of man-made neutrinos.
- “Heavy metal” detectors (iron, lead) are good at catching neutrinos.



# Can you see a neutrino ?

- You can't see a neutrino as
  - You can't catch atoms
  - If you catch one of
  - Use long distances of neutrinos
  - Intense sources of neutrinos.
- Bruno Pontecorvo. “Father” of neutrino oscillations and many ground breaking ideas in neutrino physics







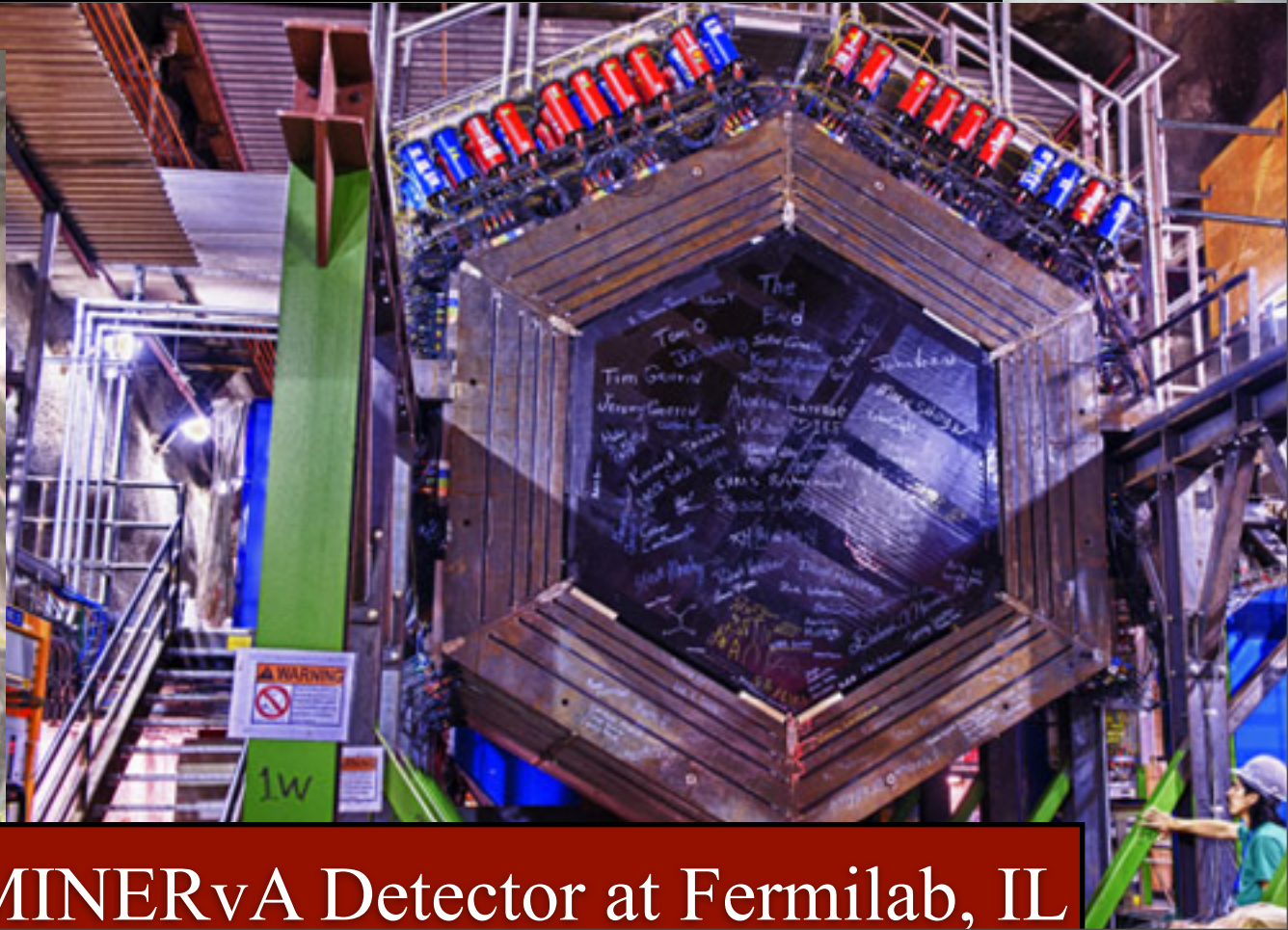
MINOS Detector at Soudan, MN



NOvA Detector at Ash River, MN



MINOS Detector at Fermilab, IL

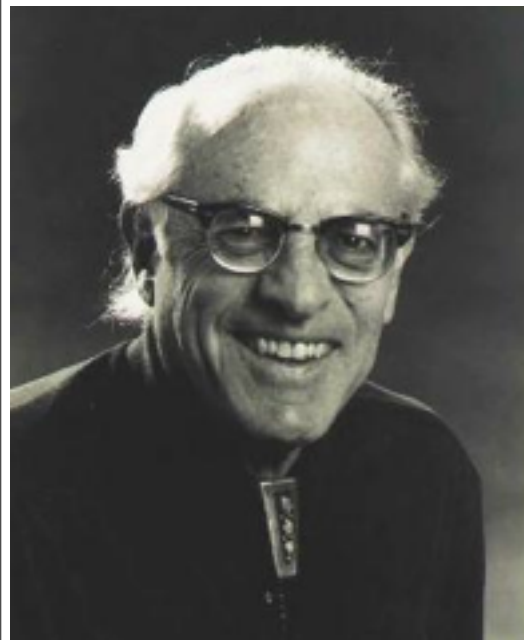


MINERvA Detector at Fermilab, IL



# Discovering the neutrino

circa 1956



Fredrick Reines



Clyde Cowan



Nobel Prize in 1995

They had worked on the Manhattan Project, radar, radiation and nuclear weapons during World War II.

“Let’s try to detect neutrinos by exploding an atom bomb !”

Project Poltergeist: to hunt down the fleeting yet haunting ghosts (neutrinos) in the world of physical reality !

Nuclear reactor was their neutrino source, so the “electron neutrino” was discovered.

$\nu_e$

# Discovering the neutrino

circa 1956

- In 1956 Project Poltergeist succeeded in recording neutrinos emitted from nuclear reactors at Savannah River, GA.
- Cadmium Chloride ( $\text{CdCl}_2$ ) solution used for detecting neutrinos !

“We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons.”

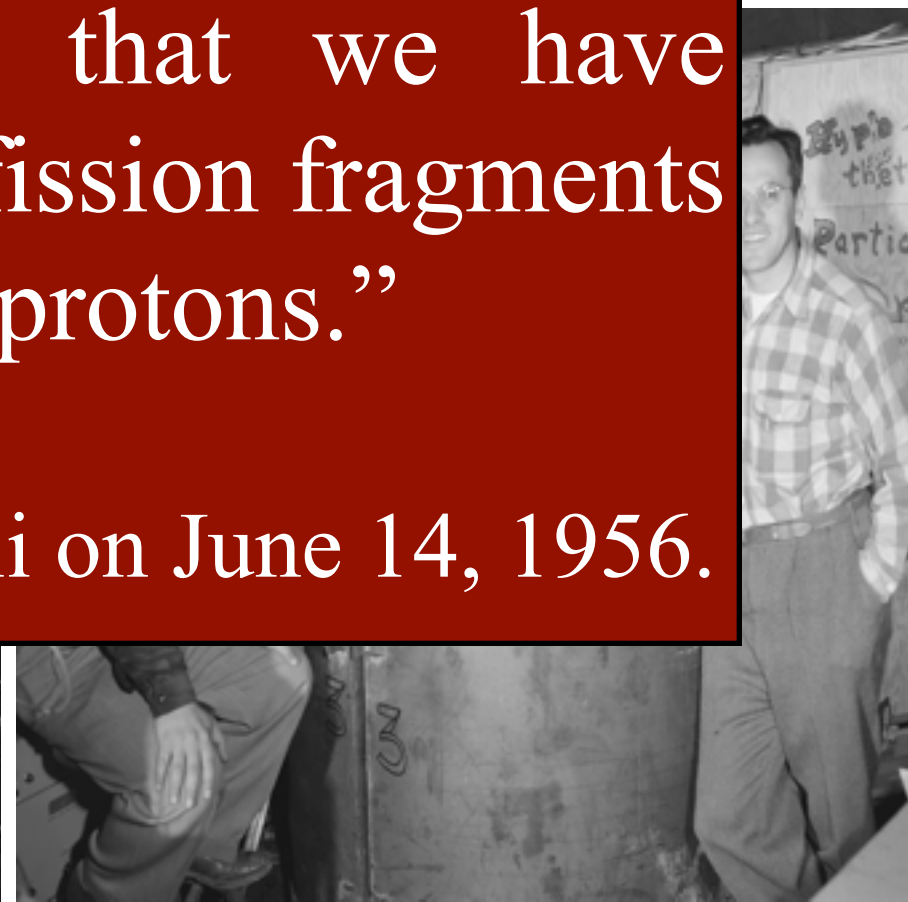
- Reines and Cowan in a telegram to Pauli on June 14, 1956.



Detector used by Reines and Cowan



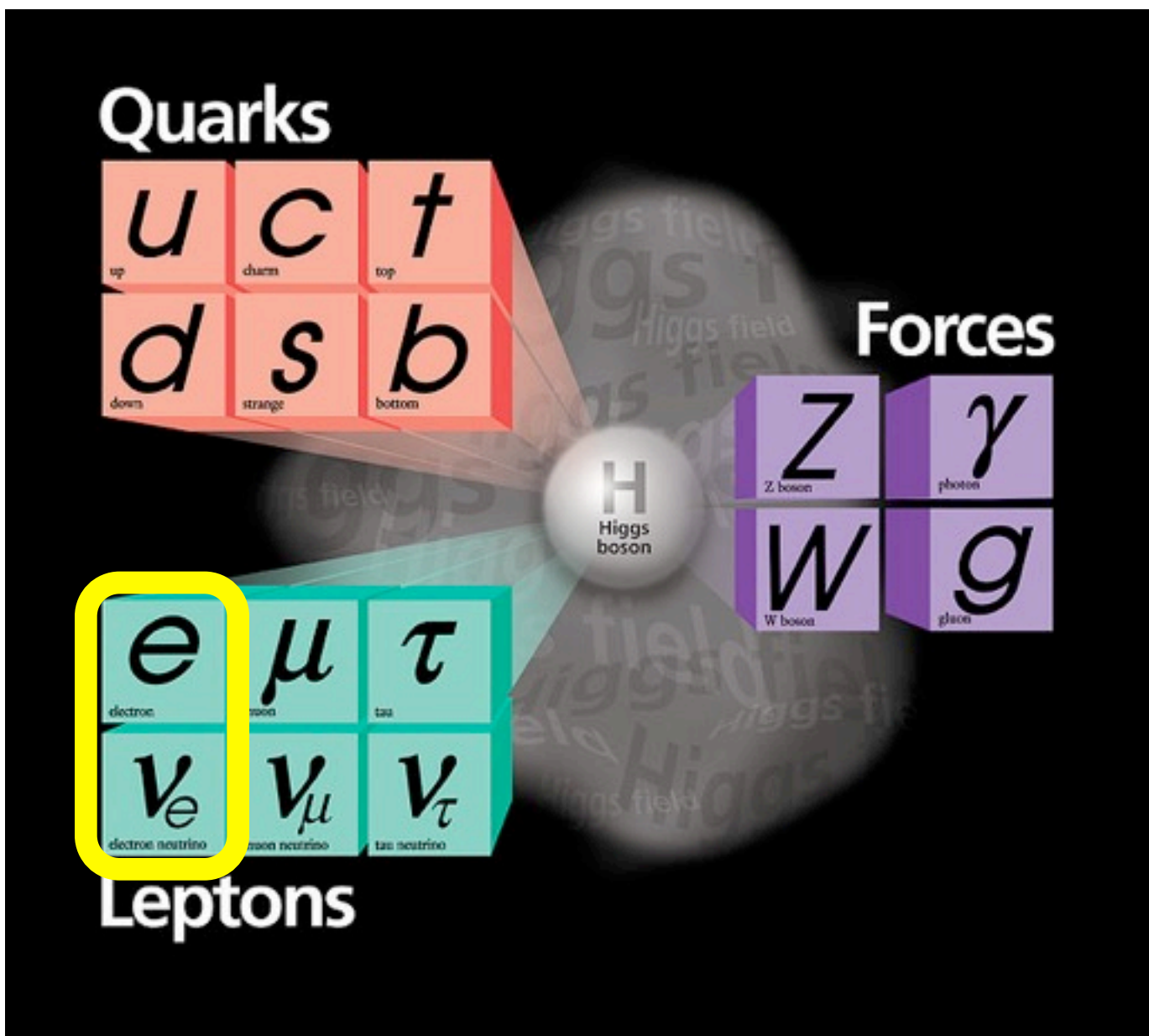
Reines and Cowan in control room



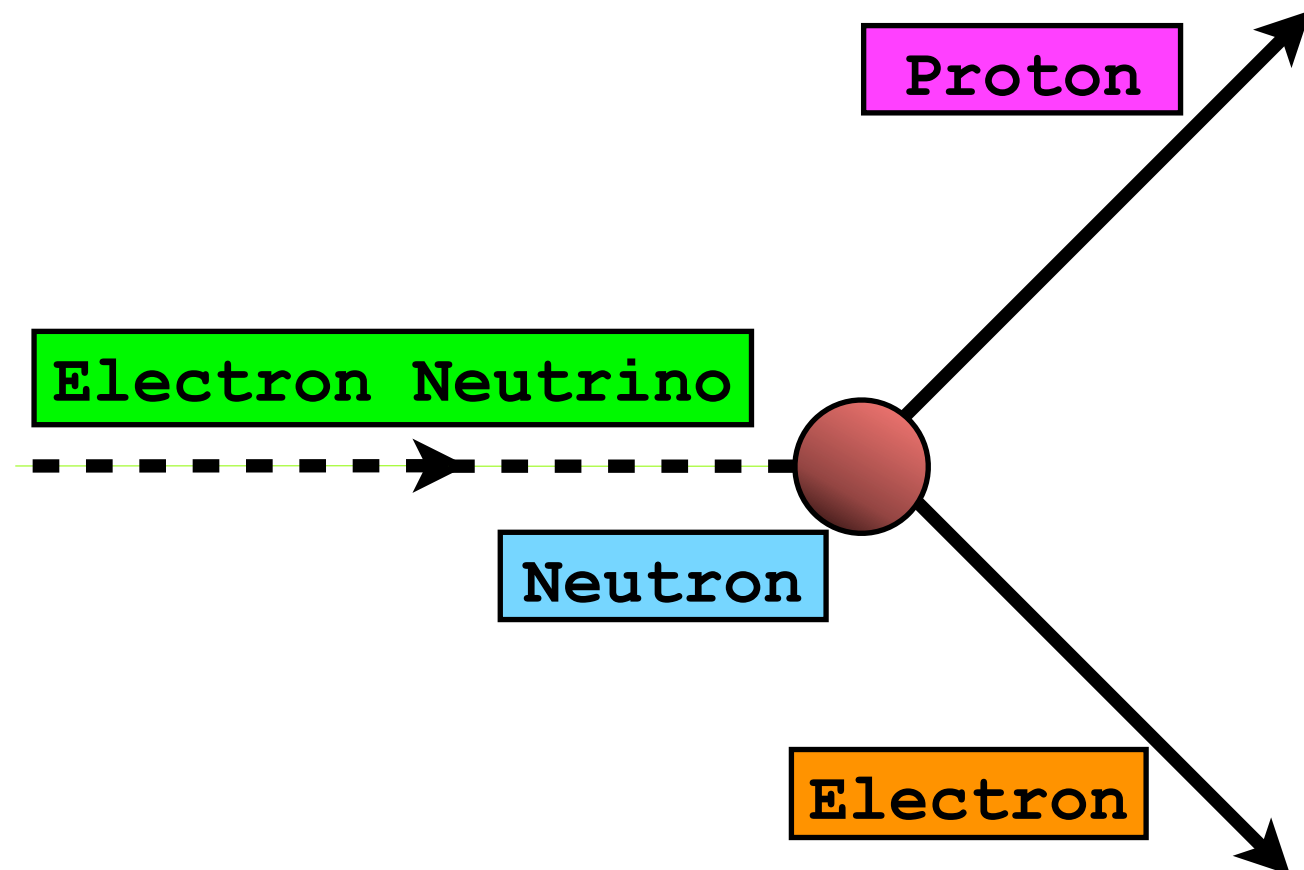
The Project Poltergeist team



# It was the “electron neutrino”



## Inverse Beta Decay

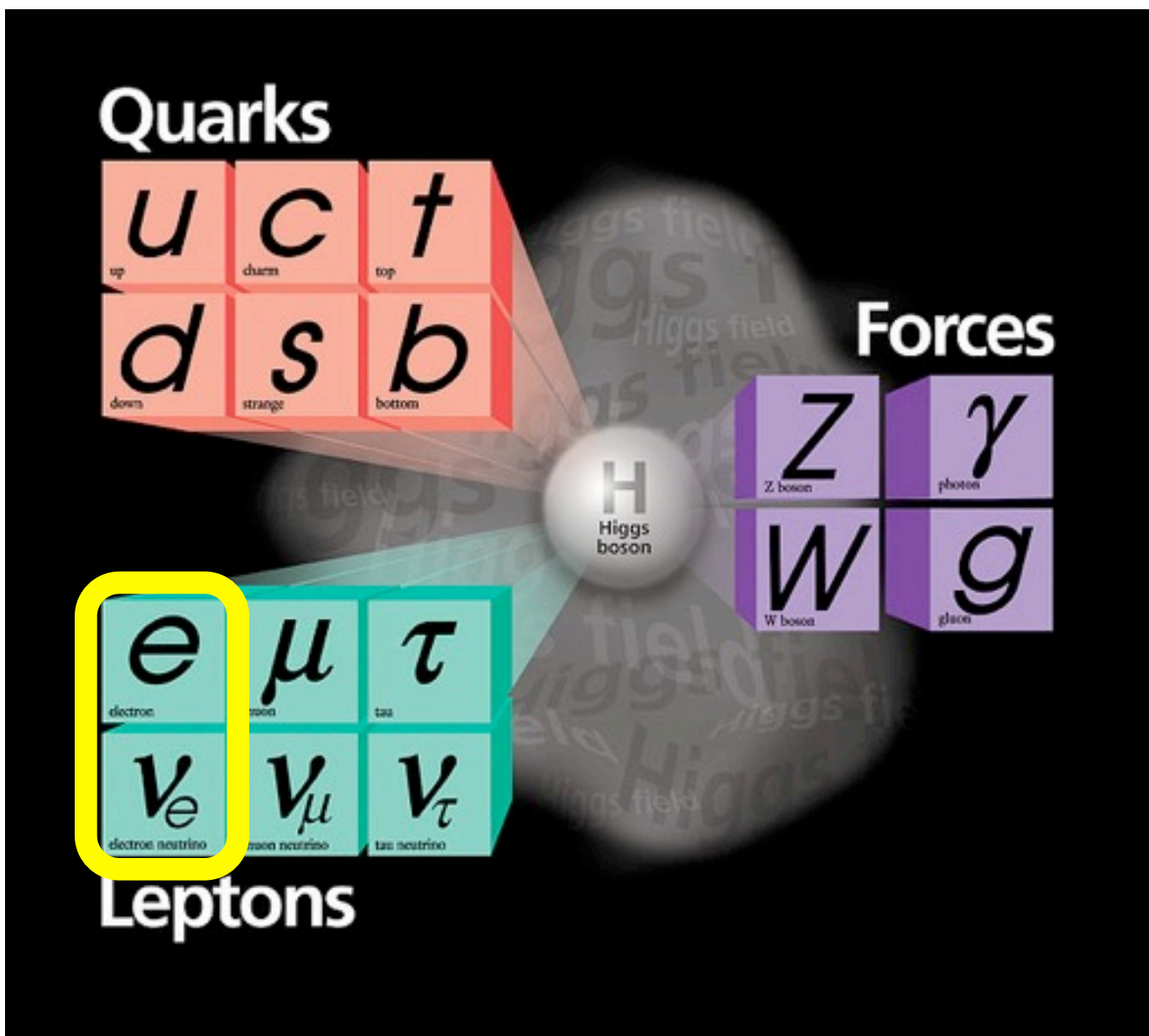


$$n \rightarrow p + e^- + \nu_e$$

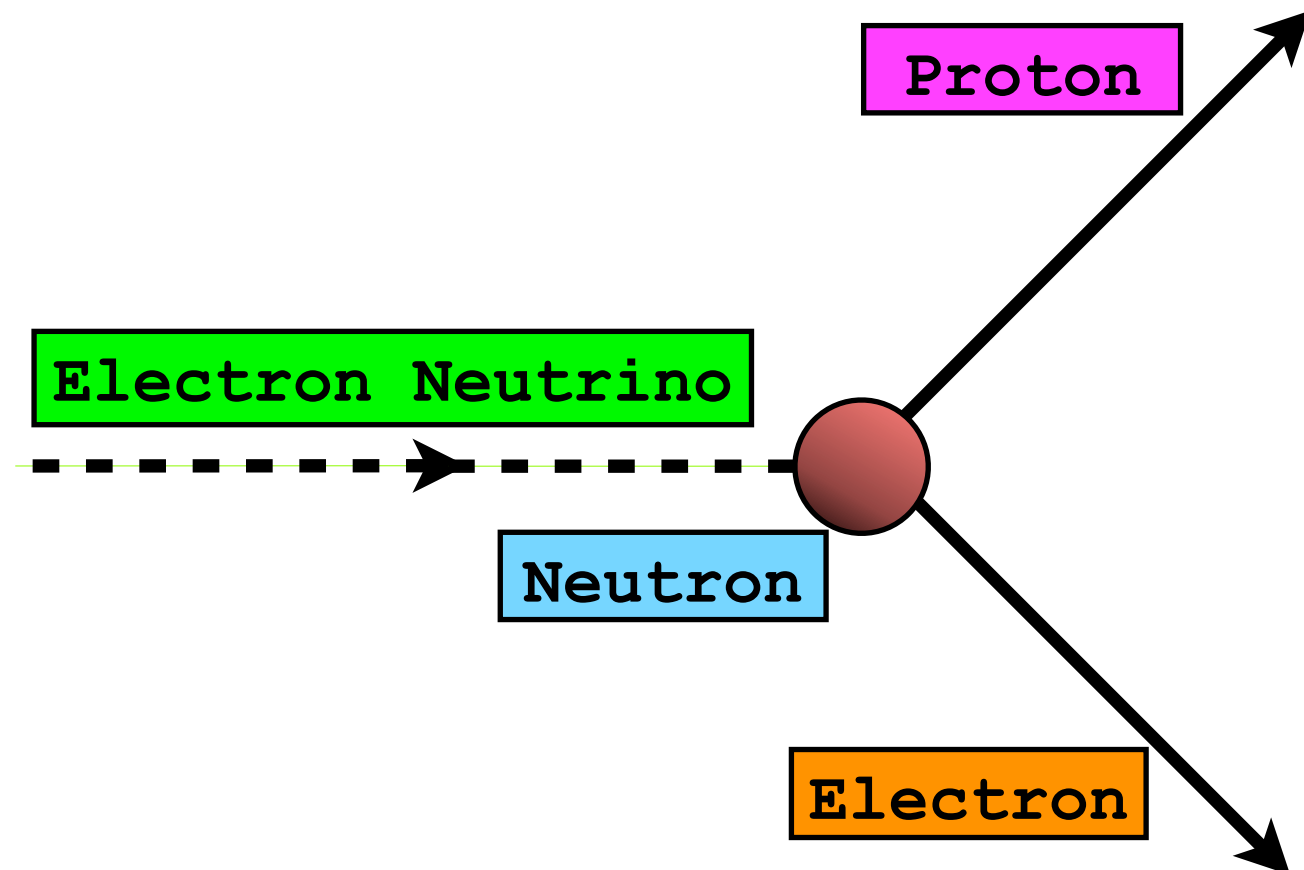
$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

# It was the “electron neutrino”



## Inverse Beta Decay



$n \rightarrow$

Electron (anti)neutrinos are produced in trillions  
at a nuclear reactor !

$+ e^-$

$+ e^+$

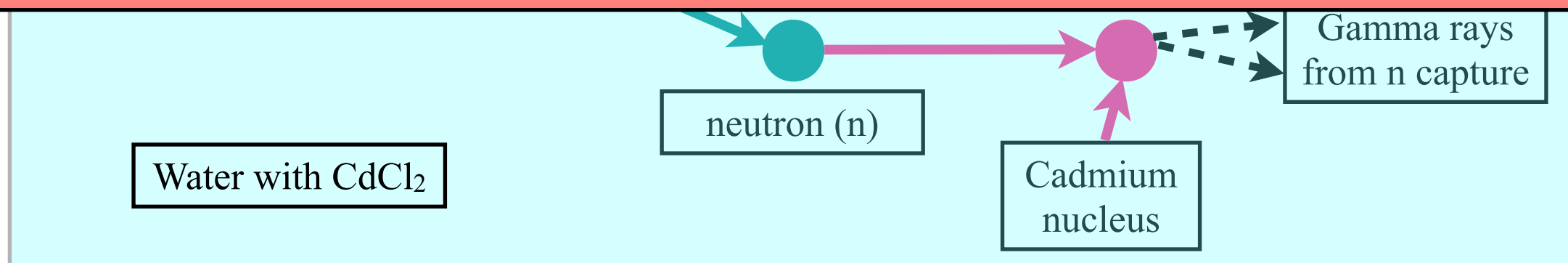


# The Poltergeist Tank

- Neutrinos interacted via the “inverse beta decay process” in the Cadmium Chloride tank.

- Years later, Reines reminded Hans Bethe about his 1934 pronouncement that “there is no practically possible way of observing the neutrino !”

Bethe’s reply was “Well, you shouldn’t believe everything you read in the papers !”

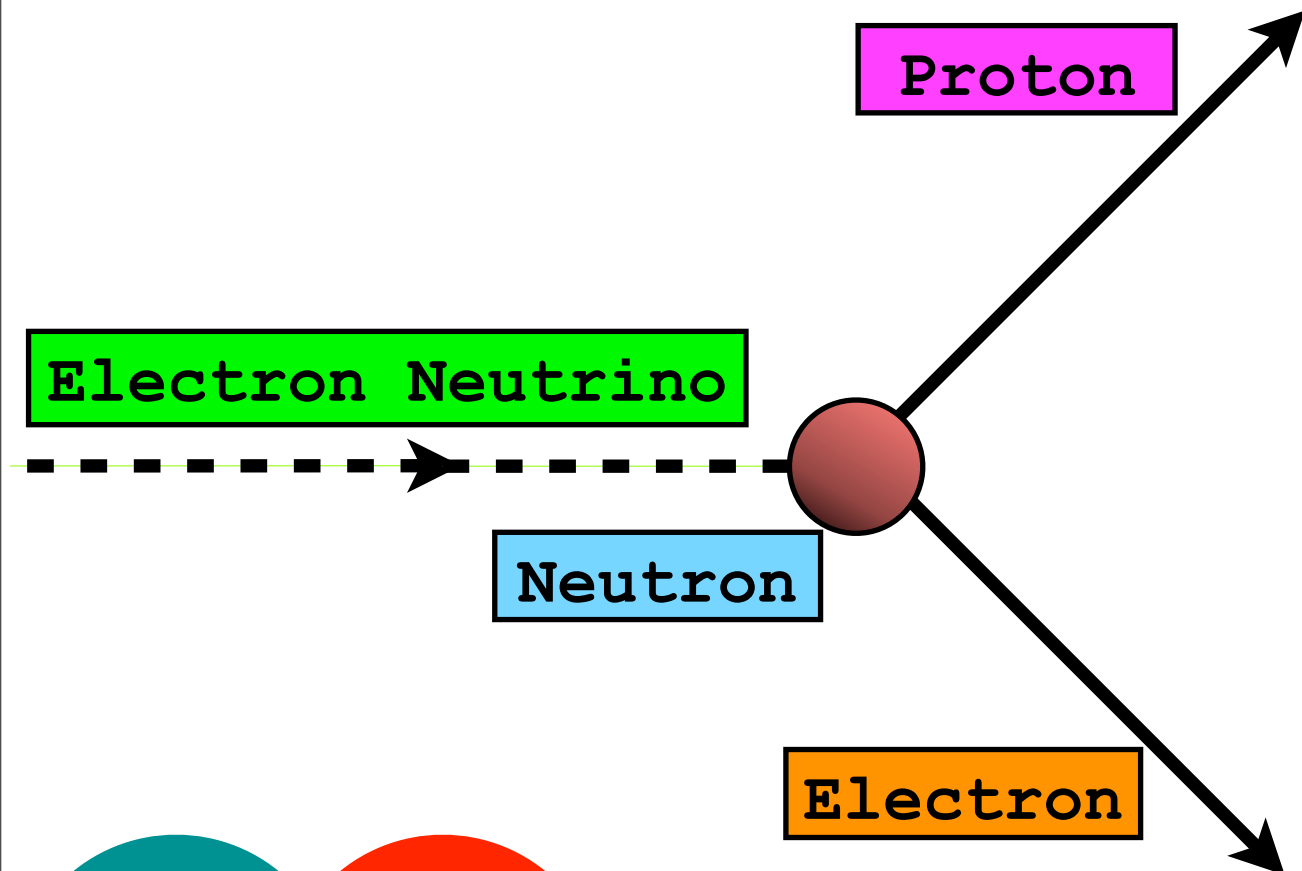


Scintillator coupled to photomultiplier tubes

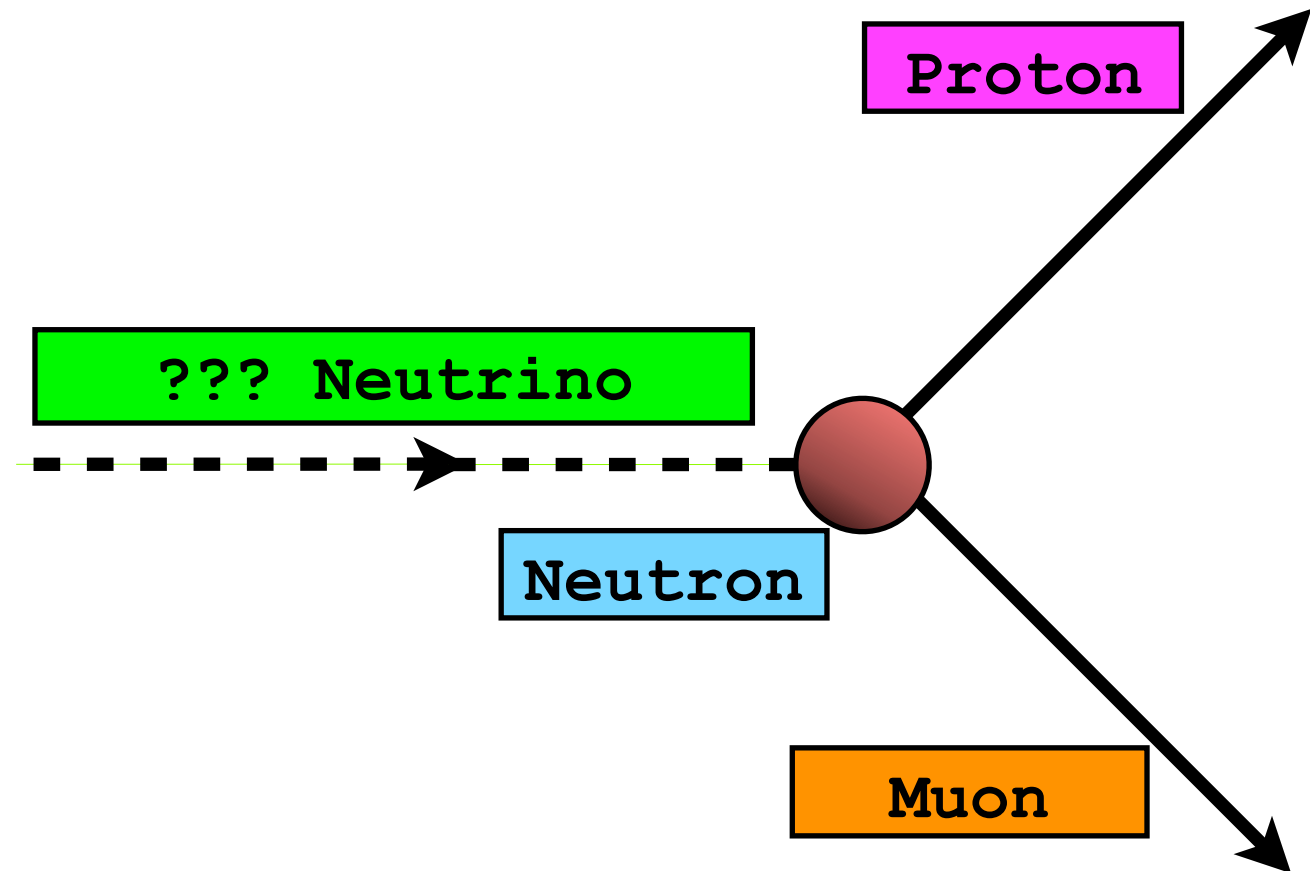


# Other neutrino types ?

Inverse Beta Decay



???



Were there neutrino partners of the lepton cousins ?

# Other neutrino types ?



Nobel Prize in 1988



L. Lederman



M. Schwarz



J. Steinberger

- Team of seven (Lederman, Schwarz, Steinberger, four students and postdocs) set to work on pion decays.
- The AGS (Alternating Gradient Synchrotron) facility at Brookhaven National Laboratory, NY was used.



# Alternating Gradient Synchrotron (1960 - present)



AGS control room, circa 1966



Building the AGS in the 1950s

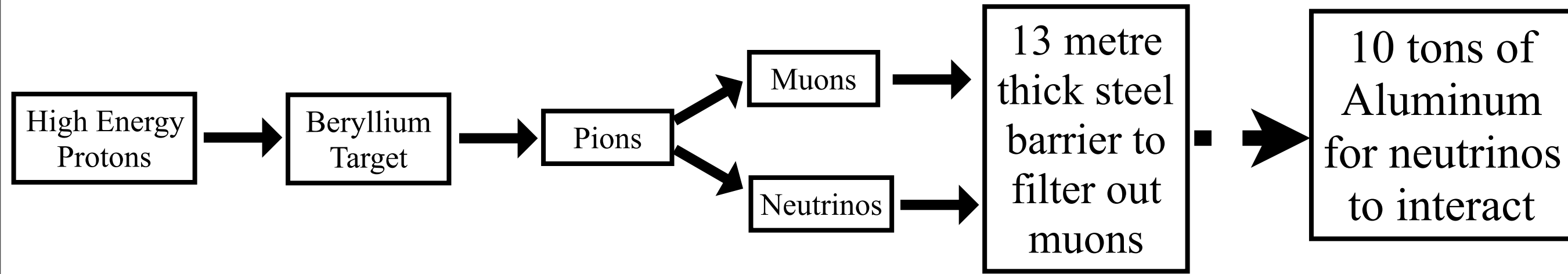
- Highest energy accelerator (33 billion electron volts) in the world until 1968 !
- Discoveries at AGS earned three Nobel Prizes !
- Still works as injector for Brookhaven National lab's colliders !
- For more information: [www.bnl.gov/about/history/accelerators.php](http://www.bnl.gov/about/history/accelerators.php)





# The Muon Neutrino

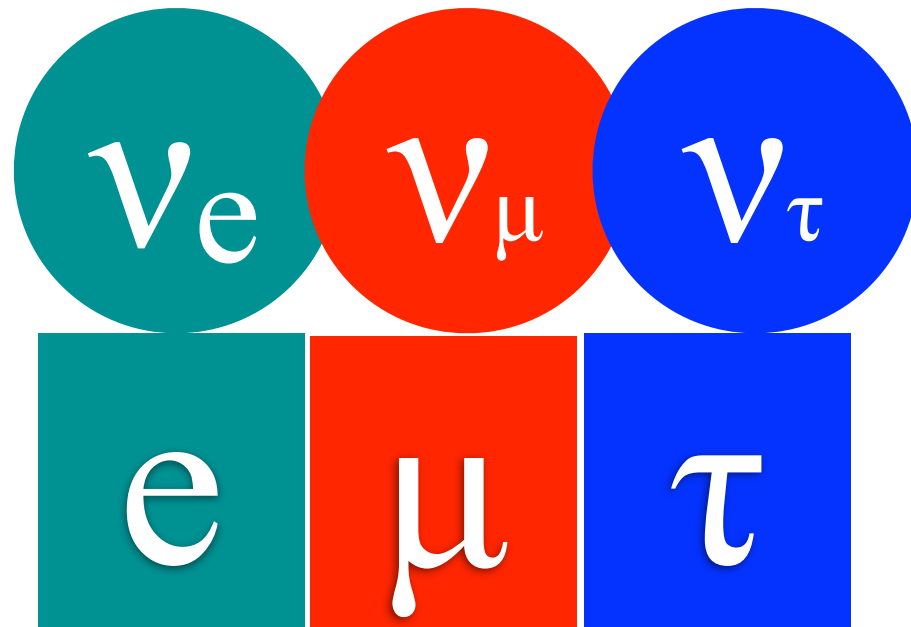
circa 1962



- If all neutrinos were of same type, they would see equal numbers of electrons and muons produced !
- More than  $10^{14}$  neutrinos passed through their detector.
  - **Only 51 hit the aluminum and resulted in a muon !**
  - **None gave an electron !**
- Muon-neutrinos and electron-neutrinos were distinct !



# The Tau Neutrino



- By 1976, Martin Perl had discovered the “tau ( $\tau$ )” lepton.
- So tau-neutrino was predicted, but it was hard to detect !
- Discovered in 2000 by DONUT experiment at Fermilab!

# Neutrinos from the Sun



- Nuclear fusion theory in stars revealed that the Sun produces vast numbers\* of neutrinos !
- Neutrinos given out from the Sun are electron neutrinos ( $\nu_e$ ).
- Solar neutrinos travel for more than 150 million km !
- Physicists thought “If I can look at these neutrinos, I can probe the heart of the Sun !”

\*about 300,000,000,000,000,000 will pass through your body during this talk



# An early neutrino fan .....



Ray Davis



John Bahcall

Davis had been searching for neutrinos from the Sun since 1952 !

Davis's detecting tank was 1500 meters deep inside a gold mine in Lead, SD.

His tank of 400,000 liters of cleaning fluid hoped to catch 1 neutrino per day !

Bahcall calculated the total number of neutrinos produced in the Sun.

How many of these solar neutrinos would Davis catch ?

# Predictions and results

circa 1968

- Bahcall's calculations showed that Davis's detector was sensitive to all high energy neutrinos from the Sun.
- Davis's results showed that he was catching **less than  $\frac{1}{2}$**  the number of neutrinos predicted by Bahcall.
- Where were the missing solar neutrinos?

$\nu_e$

There seemed to be a "solar neutrino anomaly"



Davis atop the 400,000 chlorine tank



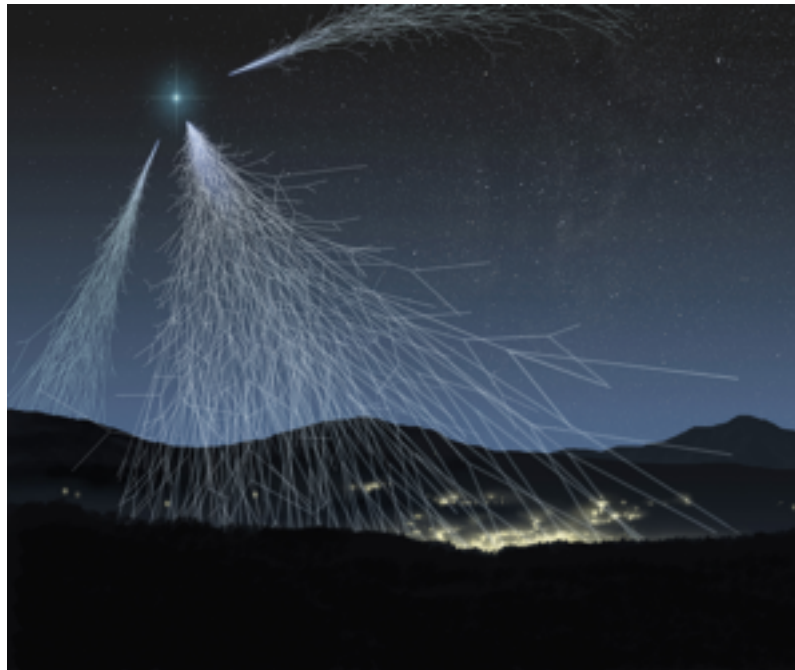
Davis inspects gas circulation pumps in the SD mine



Davis and Bahcall at their detector



# Neutrinos from the Atmosphere



- Neutrinos are produced from cosmic rays\* in the upper atmosphere !
  - Muon and electron neutrinos present  $\rightarrow \nu_{\mu} : \nu_e = 2:1$ .
- Cosmic rays can originate outside solar system, galactic sources.
- Physicists had invented technology to probe this type of neutrinos too!

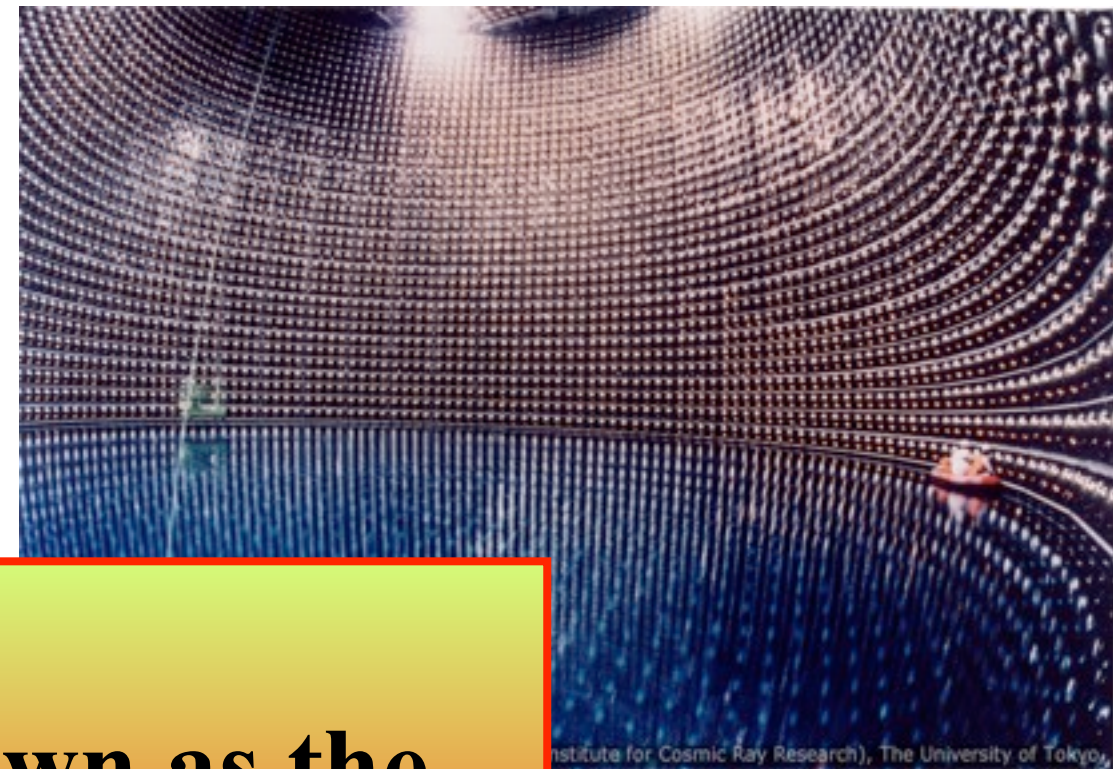
\*ultra-high-energy cosmic rays compare in energy to that of a 56 mph baseball



# Atmospheric neutrinos



SuperKamioKANDE (SuperK)  
detector in Japan



...nk with pure water

This came to be known as the  
“atmospheric neutrino anomaly”

- from cosmic  
rays were  $\nu_\mu : \nu_e = 1.1$  instead of the  
expected 2:1 !
- The further the muon neutrino traveled,  
the more likely it was to disappear !
  - Why were the muon neutrinos missing ?



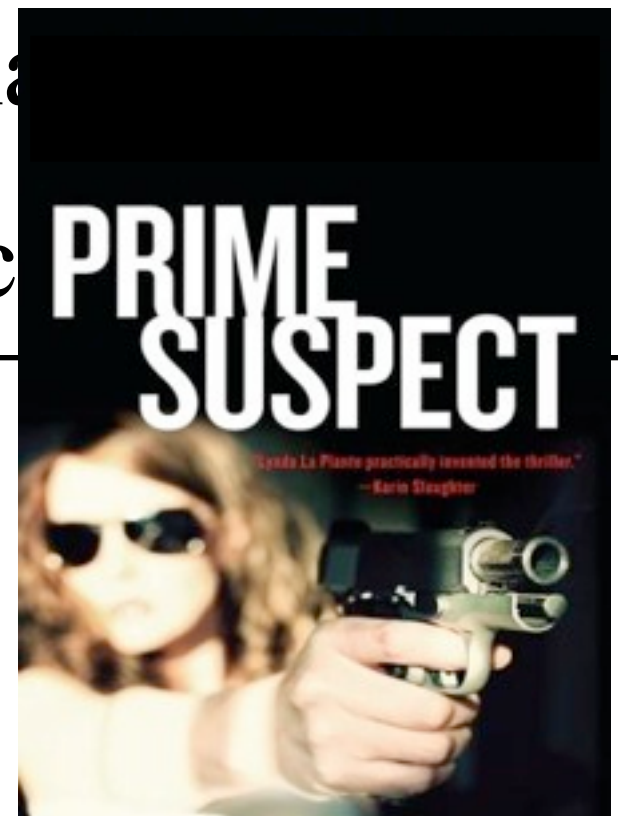
# Missing neutrinos everywhere !

- First Davis and now SuperKamiokande .....
- Total number of solar neutrinos recorded was less than half of that predicted !
- Experiments with atmospheric neutrinos also gave a different result than expected !

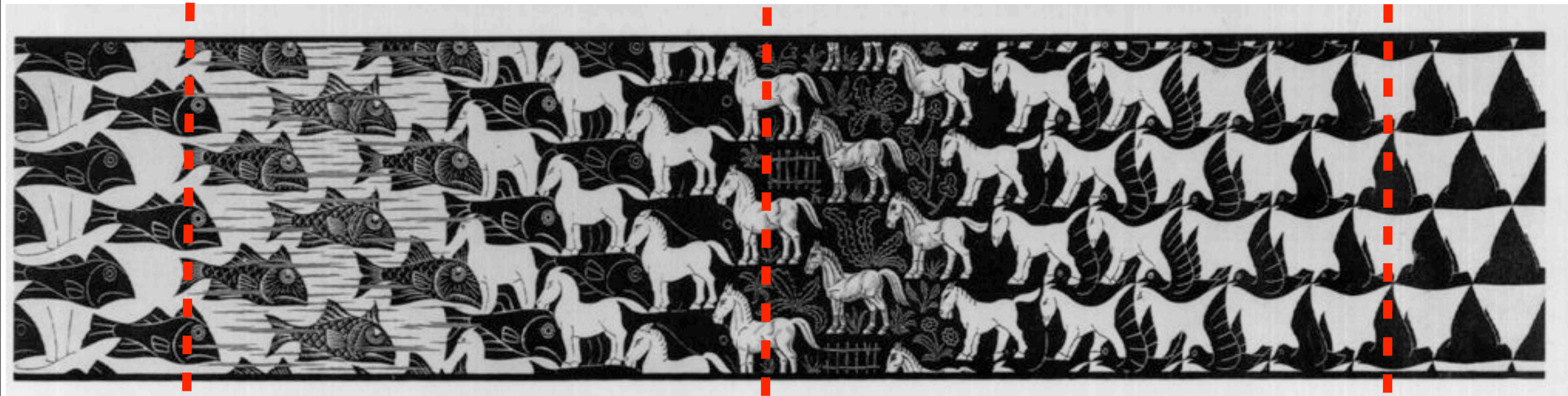
Independent experiments, similar results, common message

- Davis and Bahcall were not the mischief makers
- Sun and atmosphere did not seem like the culprits

**Could neutrinos be the prime suspects here ???**



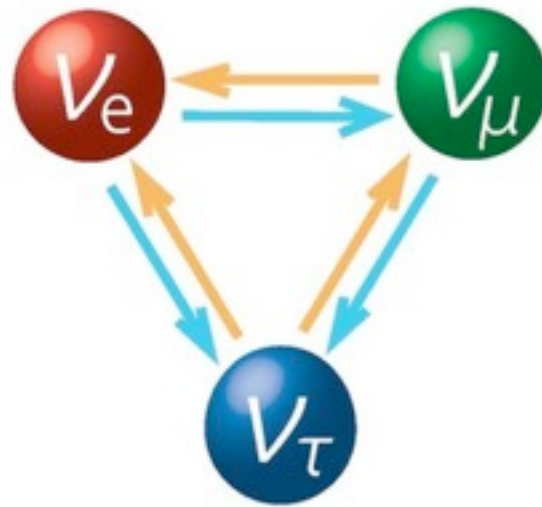
# Metamorphosis



Artist: M.C. Escher

- Were neutrinos forgetting their origin over long travel times ?
- Could an **electron neutrino ( $\nu_e$ )** born in the Sun “**change identity**” into a **muon neutrino ( $\nu_\mu$ )** ?
- How could neutrinos have this “personality disorder” ?

# Do Neutrinos oscillate ?



- Electron neutrinos emitted from the Sun had changed into other neutrino types !
- Ray Davis was detecting only those that were still electron neutrinos.
- Muon neutrinos traveling through atmosphere had changed their identity too !
- SuperKamiokande was detecting the ones that were muon neutrinos.

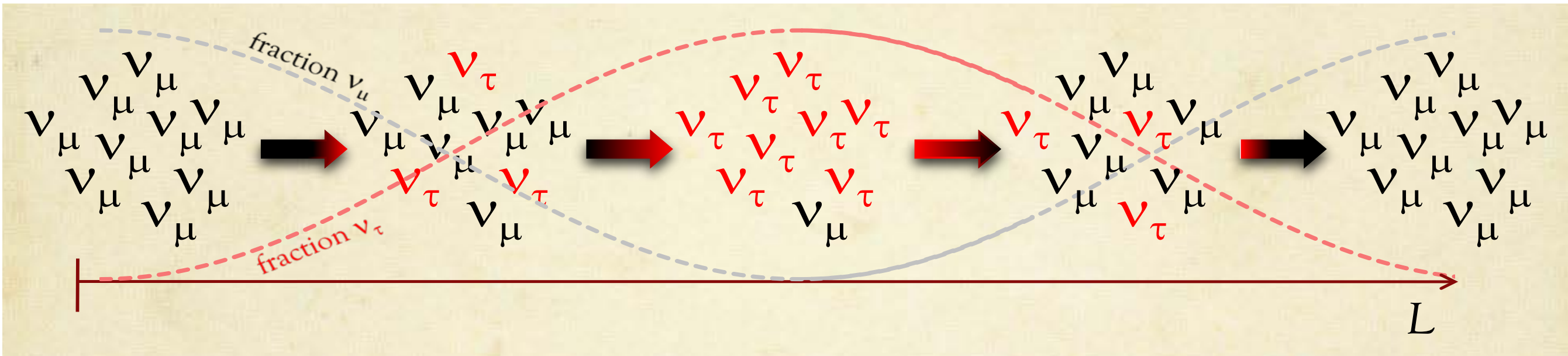
Neutrinos “oscillate” or change into another type over long distances

Neutrinos are not massless, they have mass (quantum mechanical laws) !



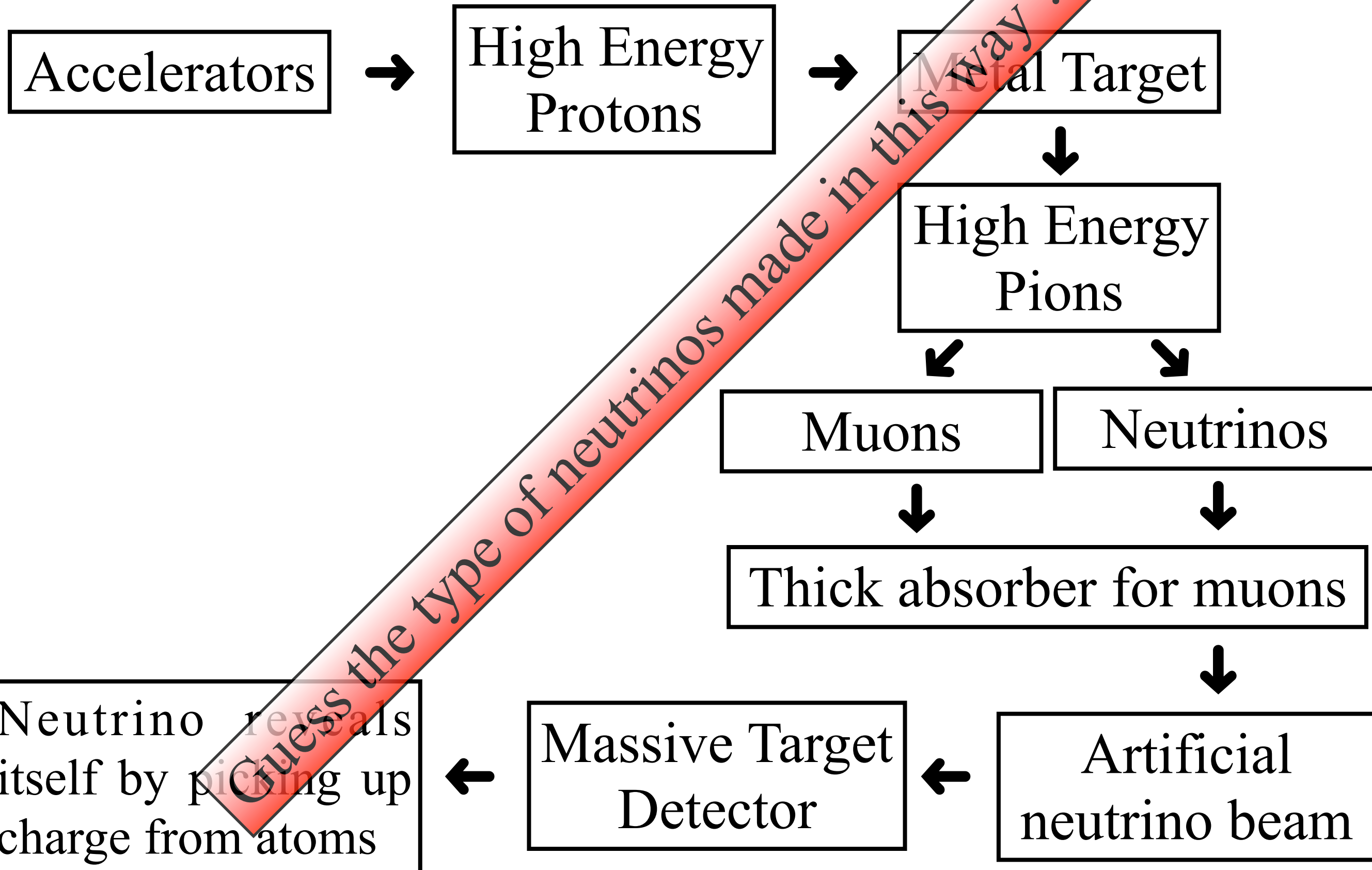
# Neutrino Oscillations

- The oscillation affects the *probability* that a neutrino is of a particular type as it travels



Important question: Can we reproduce the effects that we've seen in neutrinos from the cosmos, here on Earth in the laboratory?

# Making a neutrino beam



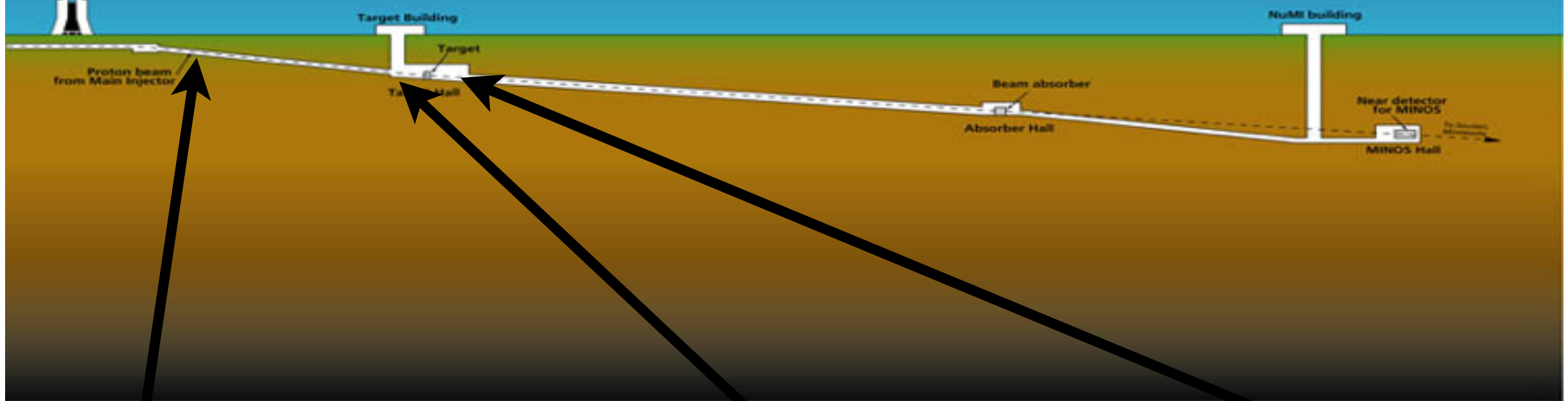
# Making Neutrinos at Fermilab

- Fermilab has two of the most intense neutrino sources in the world.
- The powerful proton accelerators called Booster and Main Injector are used for this.
- The **Booster Neutrino Beam** is made from 8 gigaelectronvolt protons from the Booster.
- The **NuMI Neutrino Beam** is made from 120 gigaelectronvolt protons from the Main Injector.





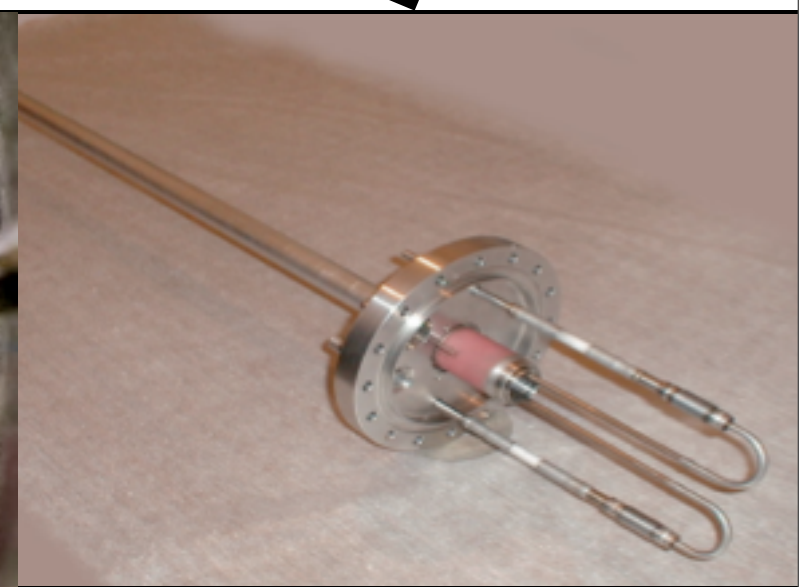
# NuMI Neutrino Beam



Main Injector tunnel at Fermilab

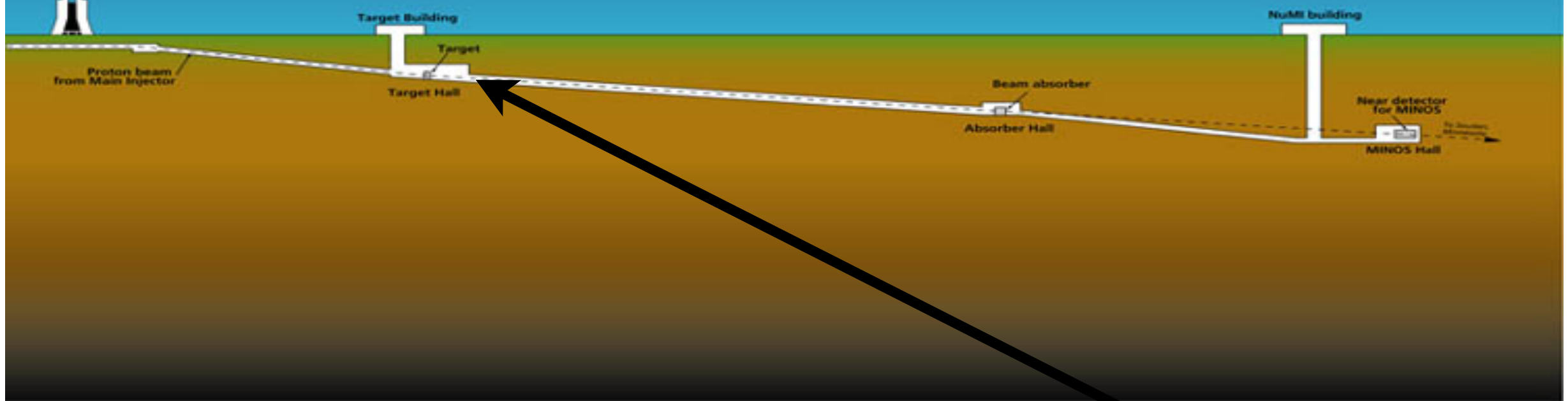


MI delivering protons to NuMI target



NuMI graphite target

# NuMI Neutrino Beam



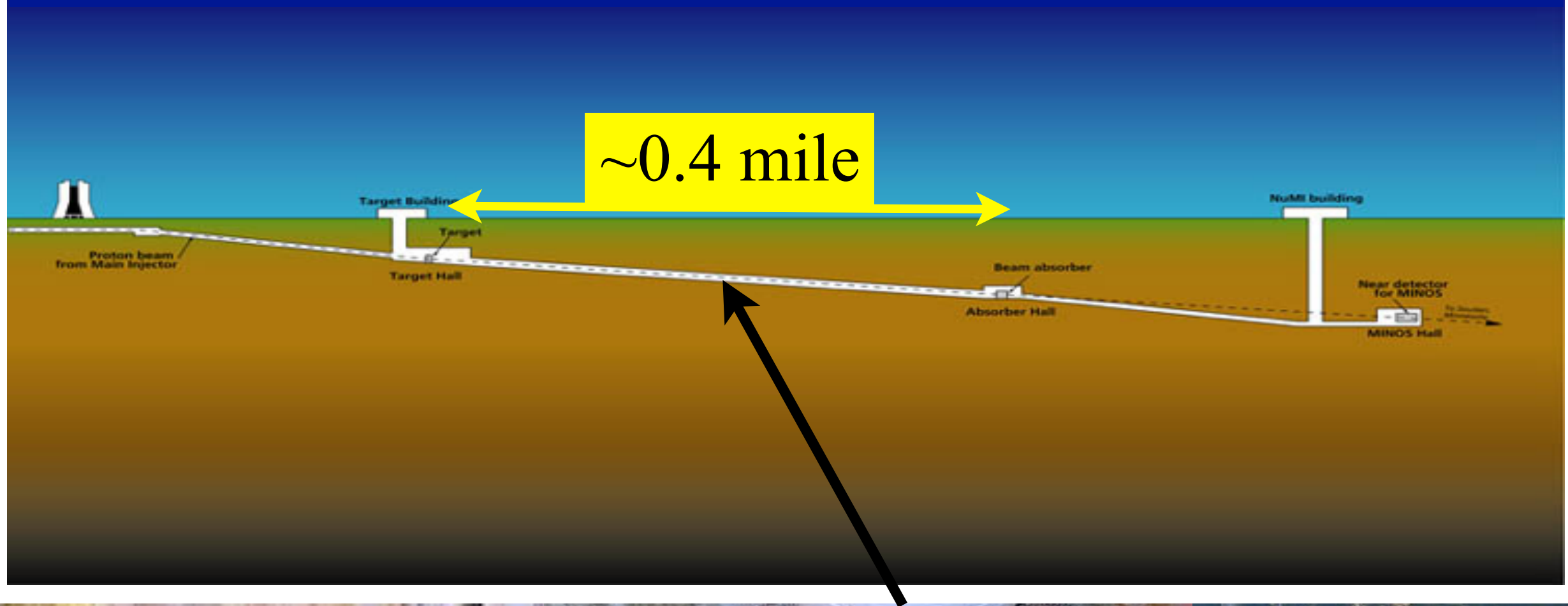
- Graphite target is hit with more than 30 trillion protons every 1.7 seconds 24 hours a day. That's more than 450 kilowatts of power.
- 2 aluminum “horns” are magnetized using 200,000 amps of current every 1.7 seconds. They focus charged particles into a beam as they pass through it.



Beam-exit end of a NuMI horn



# NuMI Neutrino Beam



NuMI tunnel boring machine



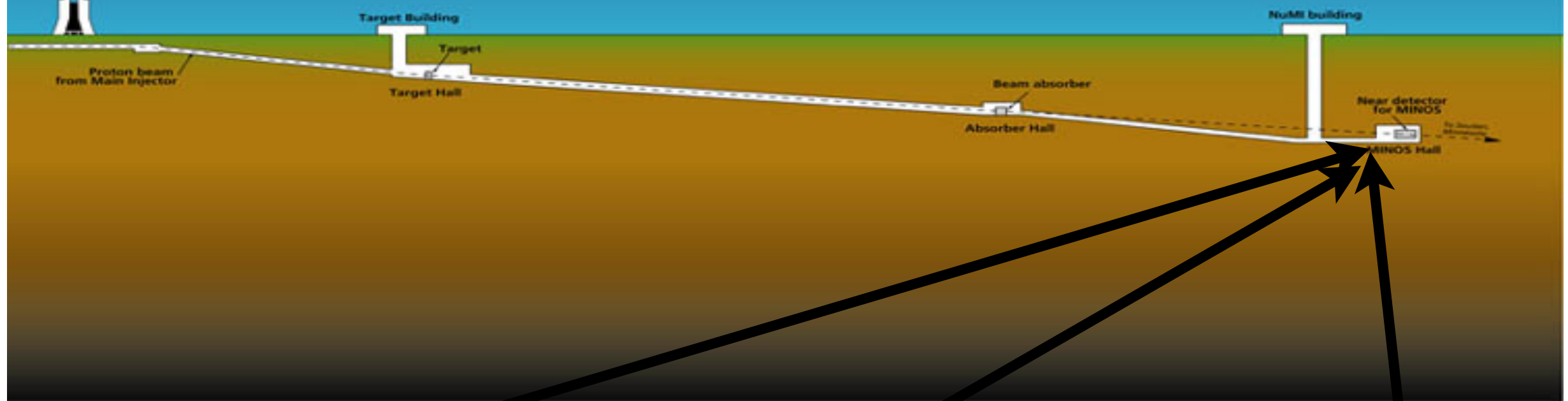
Particles decay in this pipe



Decay pipe installation



# NuMI Neutrino Beam



MINOS near detector



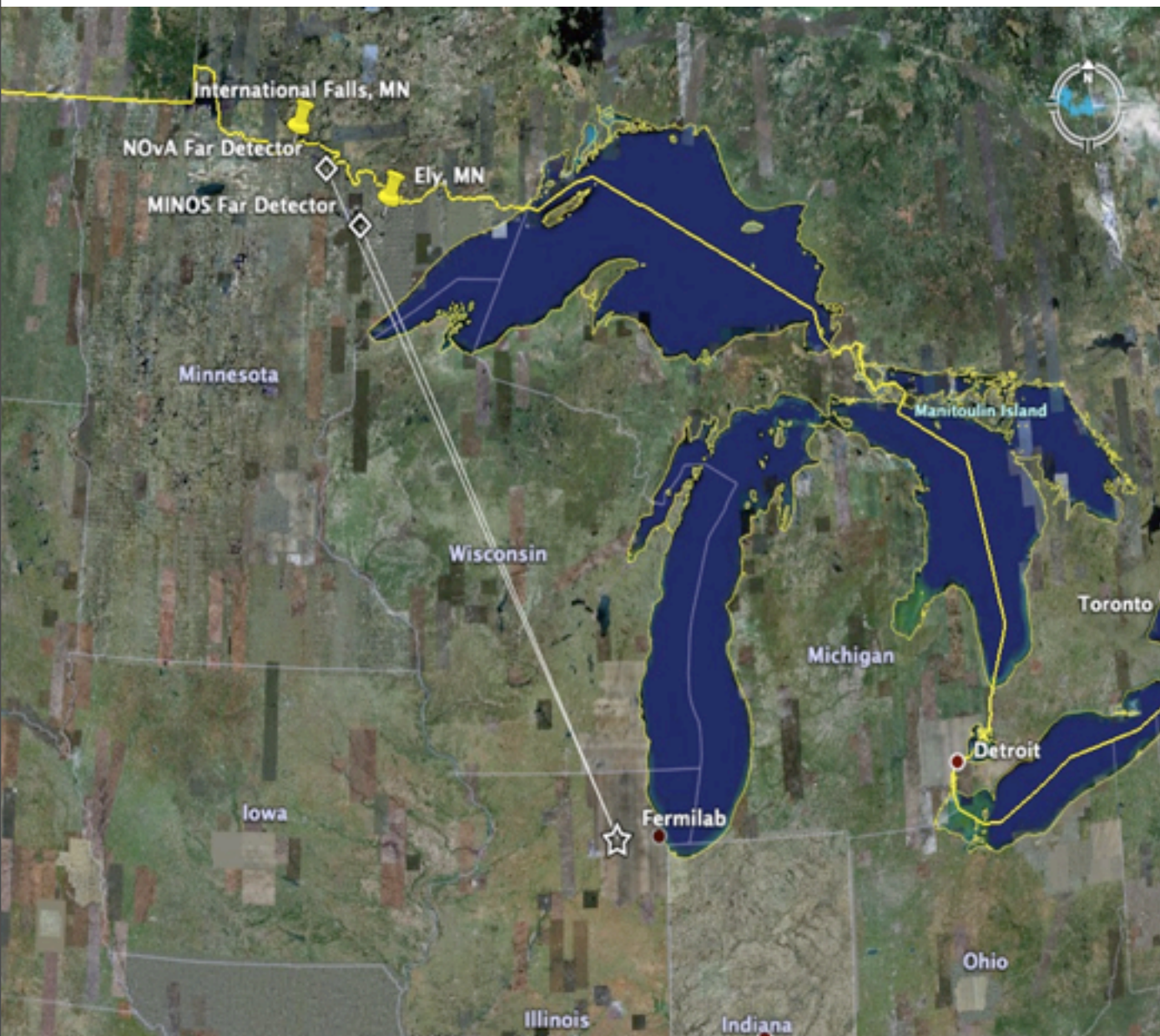
MINERvA detector



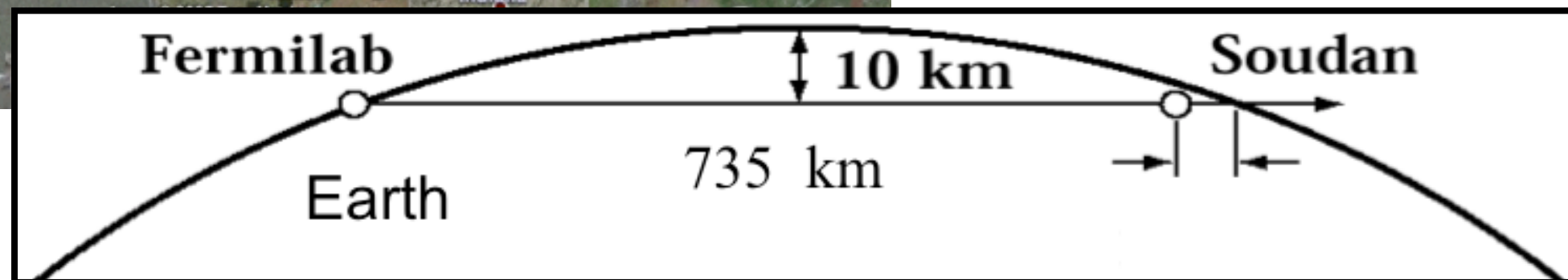
NovA near detector



# Where are the neutrinos going ?



- The NuMI neutrinos travel almost 500 miles to northern MN **in  $1/400^{\text{th}}$  of a second !**
- **No tunnel required.** Recall that Earth is like air to neutrino !
- By **comparing** the number of muon neutrinos produced at Fermilab to those that reach northern MN, we can **infer about the neutrinos that have oscillated !**





# Neutrino experiments @ Fermilab

- MINOS (Main Injector Neutrino Oscillation Search)
  - Investigates those muon neutrinos which have “disappeared” into other types !
- NOvA (NuMI Off-axis  $\nu_e$  Appearance)
  - Investigates those muon neutrinos which have oscillated into the electron type !
- MINERvA (Main Injector Experiment to study  $\nu$ -A)
  - Explores how neutrinos interact with the nuclear medium.
- MicroBooNE (Micro Booster Neutrino Experiment)
  - Will investigate various neutrino properties in great detail.

# MINOS



**MINOS Far Detector**

A photograph of the MINOS Far Detector, a large, circular, multi-layered structure made of green-painted steel beams, situated in a large industrial hall. In the background, a large, colorful, abstract mural is visible on the wall.

- Long base line experiment, neutrinos have to travel 735 km from near to far detector !
- Near and far detector count muons from the neutrinos that oscillate.
- MINOS started taking data in 2005.
- 1-2 neutrinos detected at Soudan per day.
- By 2006, a clear deficit of neutrinos was observed.



A diagram showing the baseline of the MINOS experiment. It depicts a curved path from Fermilab to Soudan, with a distance of 730 km indicated. A vertical scale bar shows 10 km.







ARE THERE MORE  
THAN THREE?  
NEUTRINO FLAVORS?



WHY DID MATTER  
WIN OVER?  
ANTIMATTER?

BIG

QUESTIONS



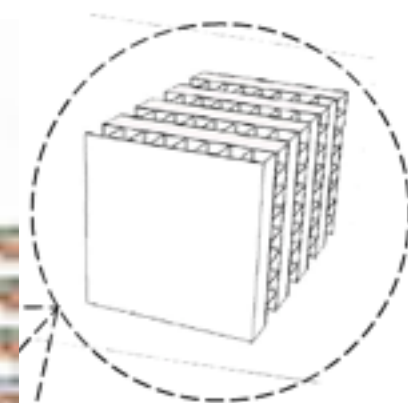
WHAT ARE THE MASSES  
OF THE THREE KNOWN  
NEUTRINO TYPES?



DOES THE HIGGS  
GIVE MASS?  
TO NEUTRINOS?



# NOvA



Approximate size of NOvA far detector in relation to Soldier Field



NOvA Near Detector

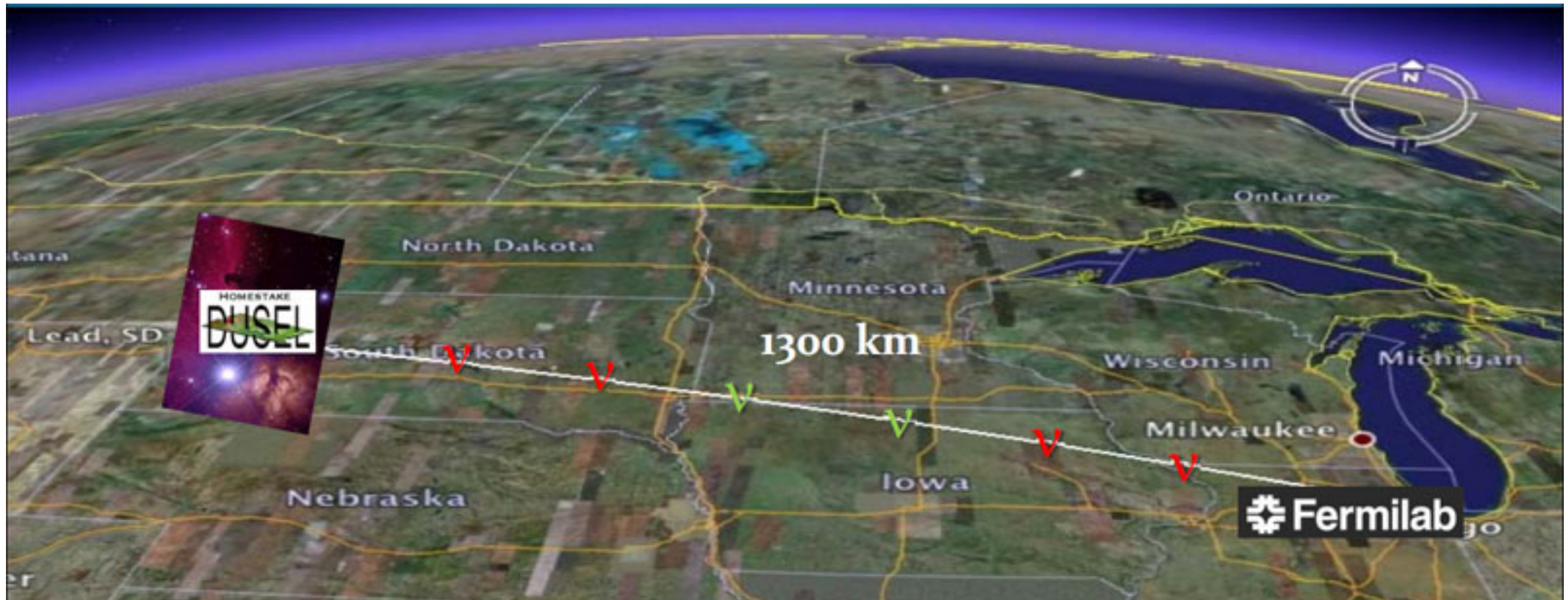


# Matter anti-matter asymmetry

- Neutrino experiments these days detect both neutrinos and anti-neutrinos
- Will show if both have the same properties (oscillate, interact) !
- If they are different can we tell something about the origins of the universe ?
- How did our matter dominated world emerge from the symmetric matter anti-matter universe that resulted from the Big Bang ?



# The DUNE Experiment



- This world class facility will carry out a compelling research program in neutrino physics.
- Fermilab will be the host for this experimental effort.
- Stay tuned for the next 15-20 years for this !



# We're aiming high here .....

Probe the contents of the universe that we cannot see via visible light or electromagnetic waves of any wavelength !

Challenge is in building the right instruments for detecting the neutrinos, measure their energies and identify their origin !

“There may be surprises awaiting us that will turn out to be even more sensational than anything that has happened so far !”

Neutrinos from far distances traveling over such immense time scales might reveal exotic properties !

Might reveal something about the Big Bang and since then !

Might reveal Physics at the Grand Unified Theory scale !

Thanks for listening !